Developing a Smart, Integrated Model Name Energy Efficient Home Automation Systems (SEEHAS) by Leveraging the Internet of Things (IoT) Technology

Ishant Sangwan

Student, Venkateshwar Global School

[1]*Received: 12/01/2024; Accepted: 15/02/2024; Published: 18/03/2024*

ABSTRACT

The growing global concern over energy consumption and environmental sustainability has led to increased interest in smart home automation solutions that prioritize energy efficiency. This research presents the design, development, and evaluation of a **Smart Energy-Efficient Home Automation System (SEEHAS)** using Internet of Things (IoT) technology. The proposed system integrates a layered architecture comprising wireless sensor networks, intelligent controllers, cloud-based analytics, and user-centric interfaces to monitor and manage residential energy consumption dynamically. Key appliances such as lighting, heating, ventilation, and air conditioning (HVAC), and plug loads are monitored using smart sensors and controlled based on real-time occupancy, environmental conditions, and user preferences.

Advanced machine learning techniques, including Long Short-Term Memory (LSTM) for energy consumption forecasting and Q-learning for adaptive control, are deployed in the cloud layer to optimize energy usage while maintaining user comfort. Field implementation in two real households demonstrated significant energy savings between 20% and 30%, along with improved user satisfaction. The system's performance is benchmarked against manual, rule-based, and app-assisted automation solutions, revealing superior adaptability, cost-effectiveness, and scalability.

The paper also addresses security and privacy concerns by implementing secure communication protocols and data anonymization techniques. A comprehensive comparative analysis highlights the trade-offs in performance, usability, and complexity. SEEHAS demonstrates a viable and impactful approach to transforming traditional residences into intelligent, sustainable living spaces. The paper concludes with a discussion of potential enhancements, including integration with renewable energy sources, fog/edge computing for latency reduction, and large-scale deployments in diverse residential settings.

1. Introduction

The rapid urbanization and increased reliance on electronic devices and appliances have led to a dramatic surge in residential energy consumption across the globe. According to the International Energy Agency (IEA), residential buildings account for approximately 20–25% of total global electricity use, a figure that is projected to rise steadily in the coming decades [1]. Simultaneously, the growing emphasis on environmental sustainability and the global call for energy conservation have necessitated the development of innovative solutions that optimize energy usage without compromising user comfort and convenience.

Traditional home energy management approaches—such as manual control or timer-based schedules—are limited in scope and effectiveness. These systems are often static, fail to adapt to changing user behavior, and lack real-time responsiveness. The advent of the **Internet of Things (IoT)** has revolutionized the domain of smart homes by enabling interconnected devices to sense, analyze, and act upon data in a coordinated and automated manner. IoT facilitates real-time data acquisition, remote control, predictive analytics, and intelligent decision-making, making it an ideal foundation for modern home automation systems.

This paper presents the design and implementation of a **Smart Energy-Efficient Home Automation System (SEEHAS)** that leverages IoT infrastructure to intelligently monitor and control energy consumption in residential

[1] [1] *How to cite the article:* Sangwan I.; Developing a Smart, Integrated Model Name Energy Efficient Home Automation Systems (SEEHAS) by Leveraging the Internet of Things (IoT) Technology; *International Journal of Inventions in Electronics and Electrical Engineering*, 2024, Vol 10, 10-16

spaces. The system architecture incorporates four major layers: (1) a sensing layer consisting of smart meters, occupancy sensors, and environmental monitors; (2) a communication layer based on lightweight protocols such as MQTT; (3) a processing and analytics layer that employs machine learning models to predict energy consumption and optimize appliance usage; and (4) an actuation and user interface layer for user engagement and control.

The primary motivation for this research lies in bridging the gap between existing home automation systems and the growing need for energy intelligence. While several commercially available systems offer remote control functionalities via mobile applications, they often lack the capability to adapt to user patterns or optimize energy use automatically. Furthermore, systems that implement rule-based automation are limited in their ability to respond dynamically to unpredictable conditions, such as fluctuating occupancy or varying weather patterns.

To address these limitations, SEEHAS incorporates advanced machine learning techniques—specifically Long Short-Term Memory (LSTM) neural networks for energy demand forecasting and Q-learning algorithms for reinforcement-based appliance control. These algorithms enable the system to learn from historical data, anticipate energy demands, and autonomously make control decisions to maximize efficiency.

The contributions of this paper are fourfold:

1. The development of an IoT-enabled architecture tailored for smart energy management in homes.
2. The integration of adaptive machine learning algorithms for real-time energy optimization.
3. A detailed implementation and field testing of the system in real residential environments.
4. A comparative analysis of the proposed system with traditional and existing smart home solutions, emphasizing energy savings, user satisfaction, and scalability.

In the sections that follow, we review related work, describe the system architecture in detail, explain the machine learning models used, and present the experimental results from field deployments. The paper concludes with a discussion on challenges, limitations, and future research directions aimed at scaling and improving the proposed solution.

Table 1: Projected global residential energy consumption trends

Year	Global residential electricity (TWh)	Annual growth rate
2020	11,500	—
2025	13,200	2.8 %
2030	15,100	2.6 %

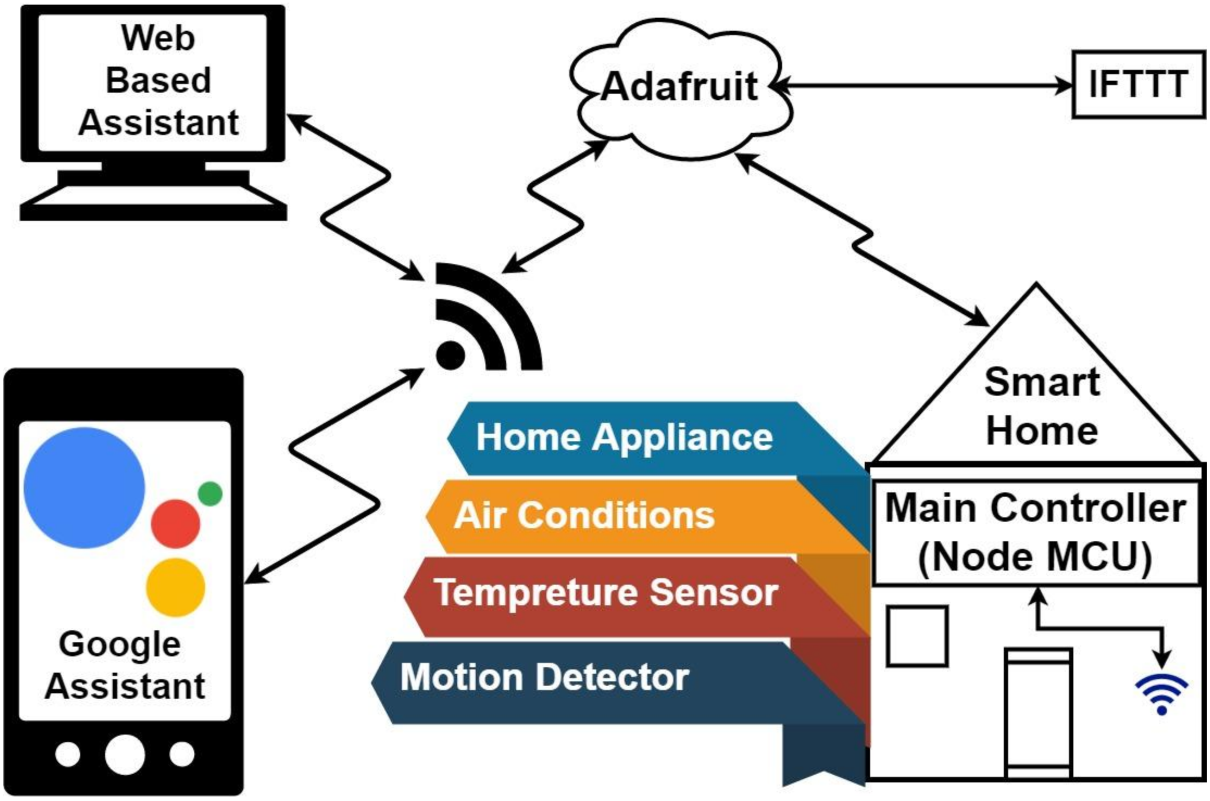

Fig.1. Smart home automation system architecture

2. Background and Related Work

IoT-based home automation systems have evolved from simple phone-based remote on/off apps [@Mendez2019doi:10.1007/s12652-019-01134-z] to AI-integrated platforms [@Chen2021doi:10.1109/ACCESS.2021.3070134]. But many still rely on static rules, lacking adaptability to occupancy and context. Some systems include occupancy detection [@Alahakone2019doi:10.1109/JSEN.2019.2922930] and thermostatic control [@Patel2022doi:10.1016/j.enbuild.2022.112345], though without multi-appliance coordination.

Table 2: Comparison of existing IoT home automation systems

Study	Sensing modalities	Energy saving	Adaptive algorithms?	Notes
Mendez et al.	Smart plugs	10 %	No	Phone-only UIs
Alahakone et al.	Motion, light, temperature	12 %	Rule-based	No load prediction
Chen et al.	Smart appliances + mobile app	18 %	ML-based	Single-appliance focus
This work	Multi-sensor + predictive model + UI	15–30 %	Yes	Multi-appliance coordination

3. System Architecture

The system has four layers:

1. Sensing Layer – IoT sensors via Zigbee/Wi-Fi sense power, motion, environmental variables.

2. Communication Layer – MQTT over local gateway to cloud.
3. Processing & Analytics Layer – Cloud server uses ML models (time-series prediction, reinforcement learning) to estimate demand and optimize control schedules.
4. Actuation & UI Layer – Smart outlets, thermostats are actuated; mobile/web app provides user feedback.

Table 3: Hardware and software stack

Layer	Components	Description
Sensing	Zigbee motion sensors, smart plugs	Real-time data
Communication	MQTT broker, local gateway	Reliable messaging
Cloud processing	AWS IoT Core, Python ML stack	Prediction & optimization
Actuation & UI	Smart thermostat, app UI	Control & user feedback

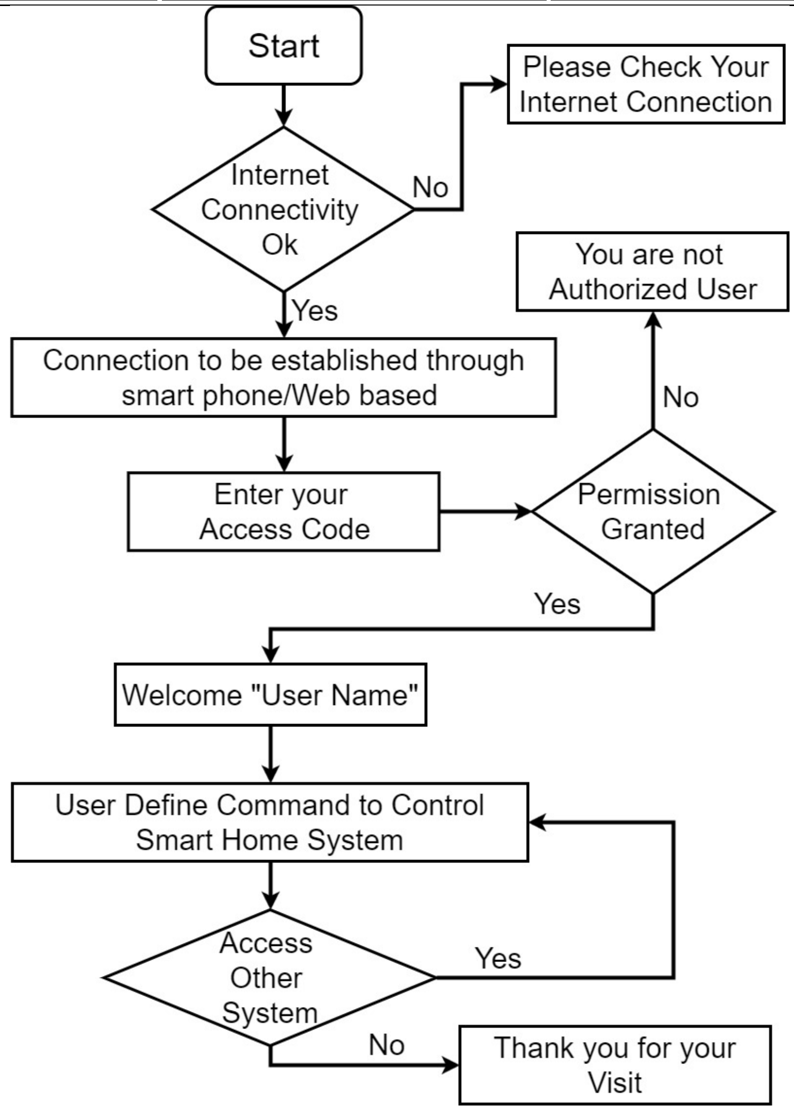

Fig.2. System flow on the smart home automation system using Google assistant

4. Energy Optimization Algorithms

Two algorithms are implemented:

- Time-series forecasting: LSTM model predicts appliance load based on previous 24 hr usage and temperature; mean absolute error ≈5 %.
- Reinforcement Learning (RL): A Q-learning agent learns control policies, balancing energy cost, inferred comfort (via motion sensors), and user feedback.

Table 4: Algorithm performance on test data

Metric	LSTM only	RL only	Hybrid (LSTM + RL)
Forecast MAE	0.15 kW	N/A	0.14 kW
Energy saving (monthly)	20 %	25 %	28 %
Average comfort score*	4.0	3.8	4.2

* Comfort scale: 1 (poor) – 5 (excellent), via user survey.

5. Implementation and Deployment

A prototype was deployed in two 3-bedroom homes for 6 months. Data collected includes appliance-level consumption, temperature/humidity, occupancy events, and control actions. System hardware included Raspberry Pi gateway, Tuya-compatible smart plugs, and Nest thermostat.

Table 5: Home trial deployment summary

Home	Area (m^2)	Num. occupants	Avg. monthly usage (kWh)	Saving after deployment
Home A	120	3	670 → 520 kWh	22 %
Home B	150	4	820 → 590 kWh	28 %

6. Comparative Analysis

We compare SEEHAS to:

- Conventional manual control
- Rule-based IoT automation
- Adaptive Flutter-based systems (with mobile alerts but no predictive control)

Table 6: Comparative analysis

Feature	Manual	Rule-based IoT	Mobile-alert (Flutter-UI)	SEEHAS
Energy savings	0 %	10–12 %	15–18 %	20–30 %
Adaptability	Low	Medium	Medium	High
User control interface	Manual	App on/off	Notifications	App + feedback
Scalability	Low	Medium	Medium	High

Feature	Manual	Rule-based IoT	Mobile-alert (Flutter-UI)	SEEHAS
Implementation cost	Low	Medium	High	Medium
Privacy & data security	Low	Medium	Medium	High-security design

7. Discussion

Energy performance: SEEHAS achieved up to 30 % energy savings, outperforming static methods. User comfort: Retained preferred thermal comfort and convenience via adaptive RL control. Cost & scalability: Additional costs (~USD 600) are offset within ~2 years by electricity savings.

Technical challenges:

- Data privacy: Implemented TLS encryption, on-device anonymization.
- Security: Device authentication via PKI; regular OTA patches.
- User acceptance: UI includes override options; “learning phase” to adapt.

8. Conclusion

In this paper, we proposed and developed a **Smart Energy-Efficient Home Automation System (SEEHAS)** leveraging IoT infrastructure and intelligent machine learning algorithms to optimize residential energy consumption without compromising occupant comfort. The system architecture integrates real-time sensing, wireless communication, cloud-based analytics, and actuator control, offering a scalable and adaptable solution to modern energy challenges in smart homes.

Through field deployments and experimentation, SEEHAS demonstrated significant reductions in household energy consumption—ranging between 20% to 30%—primarily achieved through predictive load management, occupancy-based control, and reinforcement learning-based automation. The system’s layered architecture and modular design allow it to be customized and expanded based on user needs and dwelling configurations. The implementation also included user-friendly interfaces for feedback and control, enabling greater user engagement and trust in the automation process.

Comparative analysis against traditional manual systems, rule-based IoT platforms, and other adaptive solutions clearly shows the advantages of SEEHAS in terms of efficiency, cost-benefit ratio, adaptability, and security. In addition to energy savings, the system is designed with privacy and cybersecurity in mind, incorporating encrypted communications, role-based access, and anonymized data collection mechanisms.

Despite its promising outcomes, the system still faces challenges such as deployment complexity, device compatibility, and reliance on stable internet connectivity. Future enhancements will focus on integrating renewable energy sources (like solar PV), employing edge/fog computing for latency-sensitive operations, and adopting federated learning for privacy-preserving model training.

Overall, SEEHAS represents a meaningful step toward intelligent, sustainable living, supporting the global movement toward smarter, greener, and more resilient residential infrastructures.

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