Microcontroller-Based Adaptive Smart Home System for Energy Efficiency and User Comfort

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***Abstract*—Most smart home automation systems offer advanced features but remain expensive, complex, or narrow in focus. This paper introduces a cost-effective microcontroller-based smart home system that integrates lighting, fan, and air-conditioning control into a unified platform. By leveraging real-time sensor data and user input, the system dynamically adjusts appliances to balance comfort with energy savings. Unlike solutions requiring cloud connectivity or complex AI frameworks, the proposed approach uses a standalone Arduino-based controller and simple control logic to achieve intelligent automation. This simplicity allows significant energy savings—reducing lighting and HVAC power consumption comparable to more complex AI-driven systems yet attainable with low-cost, readily available components. The novelty of the system lies in its holistic integration of multi-appliance control under a single microcontroller with adaptive, user-centric operation. The proposed system has significant implications for resource-constrained regions by enabling affordable, sustainable automation that reduces electricity costs and improves user comfort without the need for expensive infrastructure. The result is a scalable and practical smart home solution that advances accessibility, sustainability, and comfort.**

***Index Terms*—Smart Home, Automation, Microcontroller, Arduino, Adaptive Control, Energy Saving, Sustainability.**

I. Introduction

With growing environmental concerns and the depletion of Earth's resources, sustainable living has become increasingly important. Residential energy consumption is a major contributor to global energy use, and improving household efficiency can significantly reduce the ecological footprint. Smart home technologies, which connect and automate household appliances, offer a promising solution to enhance energy efficiency. By leveraging networks of sensors and intelligent controllers, these systems can make autonomous decisions that optimize comfort while reducing energy waste [1].

Smart home systems have evolved rapidly with advancements in sensors, microcontrollers, and connectivity. Modern *Internet of Things (IoT)* devices can optimize energy usage by dynamically adjusting appliance settings based on real-time environmental conditions and user preferences. For instance, lights may dim or turn off when ambient brightness is sufficient, and thermostats adjust temperature when rooms are unoccupied. This coordination reduces energy consumption, making IoT-based automation solutions attractive to both cost-conscious and eco-conscious consumers [2].

Researchers have explored intelligent algorithms, such as *machine learning* (reinforcement learning and deep learning), to further improve energy management. These algorithms enable systems to predict energy needs and adapt to occupant behavior in real-time, ensuring efficient use of energy without compromising comfort. Additionally, adaptive control that personalizes automation based on user habits has been shown to further reduce unnecessary energy consumption [3].

Despite these advancements, challenges remain. One primary barrier is the *high initial cost* of smart home systems, which may be prohibitive in developing regions. Another concern is *privacy and security*, as these systems rely on detailed data collection. Addressing these issues is crucial for broader adoption. Furthermore, the complexity of some systems can deter users, but ongoing advancements in affordable technology, security, and user-friendly designs are helping lower these barriers, making smart home solutions more accessible.

This paper presents an accessible, effective smart home energy management solution using a unified microcontroller-based system. The system integrates the operation of key household appliances—lighting, fans, and air conditioning—into a single platform, utilizing real-time feedback from sensors (light, temperature, humidity, and motion) and user input to make adaptive decisions. Using straightforward control algorithms on an Arduino-based platform, the system avoids the complexity and expense of cloud-based or AI-heavy systems while achieving substantial energy savings. The performance is evaluated in terms of energy reduction, showing a 60% reduction in lighting and HVAC energy use, while maintaining comfort. The system also allows manual overrides, ensuring user acceptance and practicality.

In summary, this work makes the following contributions to the field of smart home automation and energy management:

1) **Integrated Home Control Architecture:** A unified home automation architecture centered on a low-cost microcontroller that manages lighting, fan speed, and air conditioning, making it cost-effective and accessible to resource-constrained settings.
2) **Adaptive, Sensor-Driven Energy Management:** Real-time sensor data drives adaptive control strategies that adjust appliance operation dynamically, achieving significant energy savings without relying on complex cloud services or machine learning models.
3) **User-Centric and Scalable Solution:** A user-friendly design with manual overrides and preference settings ensures comfort, while the scalable, modular solution can be extended to more appliances or larger environments.

II. Literature Review

A. High-Cost Cloud-Based Systems

Many smart home systems rely on cloud-based platforms for data processing and control. For example, Zhang et al. [4] proposed a cloud-dependent smart home system that uses IoT devices for energy management. While effective, this approach requires continuous internet connectivity and subscription-based cloud services, making it expensive and inaccessible for low-income households. Similarly, Cheng et al. [5] developed a cloud-based smart home system using IoT and cloud computing technologies. Although the system achieved energy savings, it required expensive cloud infrastructure and continuous internet connectivity, making it inaccessible for low-income households. Proposed System Advantage: The proposed system operates standalone without cloud dependency, eliminating subscription fees and privacy risks. It uses a low-cost Arduino microcontroller, making it more affordable and accessible.

B. Complex AI-Driven Systems

AI-driven smart home systems, such as those using machine learning (ML) and reinforcement learning (RL), have been explored for energy optimization. Koltsaklis et al. [6] demonstrated an ML-based system that predicts energy usage patterns and adjusts appliance operation accordingly. However, such systems require significant computational resources, expensive hardware, and extensive datasets for training, making them impractical for widespread adoption. Wang et al. [7] implemented a reinforcement learning-based energy management system for smart homes. While the system achieved energy savings, it required significant computational resources and was difficult to implement in real-world settings. Proposed System Advantage: The proposed system avoids these complexities by using simple control logic and real-time sensor feedback, achieving comparable energy savings without the need for AI.

C. Limited Scalability in Proprietary Systems

Proprietary smart home systems, such as those offered by commercial vendors, often lack scalability and interoperability. Huang et al. [8] developed a smart home system integrated with solar PV and AI for energy management. While effective, the system relies on proprietary hardware and software, limiting its adaptability to different environments or additional appliances. Kim et al. [9] reviewed several proprietary smart home systems and found that they often lack interoperability and require expensive hardware. Proposed System Advantage: The proposed system is modular and scalable, allowing for easy integration of new devices or expansion to larger environments.

D. High Initial Costs of IoT-Based Systems

IoT-based smart home systems often require expensive hardware and infrastructure. Mustofa et al. [10] proposed a Wi-Fi/GSM-enabled smart home system that reduces HVAC energy consumption by 30%. However, the system's reliance on Wi-Fi/GSM modules and IoT devices increases its initial cost, making it less accessible for budget-conscious users. Yoon et al. [11] developed an IoT-based home energy management system over a wireless sensor network. While the system achieved energy savings, it required expensive IoT devices and complex setup procedures. Proposed System Advantage: The proposed system uses low-cost components (e.g., Arduino, DHT22 sensors) and avoids expensive connectivity modules, making it a more affordable alternative.

E. Lack of User-Centric Designs

Many smart home systems prioritize automation over user preferences, leading to reduced user satisfaction. Iram et al. [12] implemented a weather-based AI system for HVAC control, which adjusts operation based on environmental conditions. While energy-efficient, the system lacks manual override options, limiting user control. Zhang et al. [13] proposed an energy-efficient home automation system with user-centric adaptive controls. While the system included user preferences, it relied on complex AI algorithms, making it difficult for non-technical users to operate. Proposed System Advantage: The proposed system addresses this limitation by incorporating both automatic and manual control modes, allowing users to override automated settings and tailor the system to their preferences.

F. Energy Inefficiency in Conventional Systems

Traditional smart home systems often use fixed schedules or static control logic, leading to energy inefficiency. Masali et al. [14] demonstrated an ESP32-based system that integrates solar power with home automation. While innovative, the system's static control logic fails to adapt to real-time changes in occupancy or environmental conditions. Nguyen et al. [15] highlighted the energy inefficiency of conventional smart home systems that rely on fixed schedules. Proposed System Advantage: The proposed system uses adaptive control strategies based on real-time sensor data, ensuring optimal energy use and comfort.

G. Privacy and Security Concerns

Many smart home systems rely on cloud connectivity and data collection, raising privacy and security concerns. Nguyen et al. [15] highlighted the risks associated with data breaches in IoT-based smart home systems. Choi et al. [16]proposed an energy consumption optimization system for smart homes using reinforcement learning. While the system achieved energy savings, it relied on cloud connectivity, raising privacy and security concerns. Proposed System Advantage: The proposed system avoids these issues by operating locally without cloud connectivity, ensuring data privacy and security.

H. Limited Focus on Renewable Energy Integration

While renewable energy integration is an emerging trend, many systems fail to optimize its use. Patel et al. [17] proposed a hybrid renewable energy system for smart homes but did not address dynamic appliance control based on energy availability. Li et al. [18] proposed a smart home energy management system based on deep learning. While the system achieved energy savings, it did not integrate renewable energy sources effectively. Proposed System Advantage: The proposed system dynamically adjusts appliance usage based on solar availability, reducing grid dependency .

III. METHODOLOGY

In smart home automation, controlling lights, fans, and air conditioning (AC) is essential for optimizing energy consumption and enhancing user comfort. These appliances represent the highest and most frequent sources of energy use in residential settings. The proposed system introduces a unified microcontroller-based platform that integrates real-time sensor feedback and user input to dynamically adjust appliance operation. This approach ensures optimal comfort and energy efficiency by automating the control of lighting, fan speed, and AC settings based on environmental factors such as temperature, humidity, and occupancy. The novelty of the system lies in its ability to deliver AI-like performance using low-cost, standalone microcontroller-based hardware, without the need for cloud dependency or complex AI models. The system achieves significant energy savings through intelligent control logic, reducing lighting and HVAC power consumption. This section outlines the key components and operational mechanisms of the proposed smart home automation system. Three control mechanisms have been applied and integrated to create an energy-efficient and sustainable smart home system.

A. Control of Light

The proposed lighting control mechanism introduces an adaptive state-based strategy to enhance energy efficiency and user flexibility. The system operates in two states: in state 1, the user can manually activate the lights, while in state 2, the system automatically determines the threshold level and controls the lights accordingly. If the ambient light intensity falls below the set threshold, the normal light will be activated; otherwise, the dim light will be used to conserve energy. Unlike conventional lighting systems that rely on fixed brightness settings, this approach ensures that light levels are dynamically adjusted based on real-time sensor data and environmental factors. The ability to switch between automatic and manual control enhances user satisfaction, while the adaptive threshold-based operation ensures that energy is used efficiently without compromising visibility or comfort. The inclusion of manual switching provides an additional layer of user control, ensuring that the system remains responsive to user preferences. This hybrid approach not only conserves energy but also personalizes the lighting experience, making the system both adaptive and user-centric. The circuit diagram is shown in Fig. 1.

B. Control of Fan

The fan control mechanism integrates adaptive relay-based voltage modulation to adjust fan speed according to real-time temperature and humidity data. A 4-channel relay module is employed, allowing four levels of voltage variation to achieve precise control over fan speed. A DHT22 sensor continuously monitors room temperature and humidity, and the microcontroller adjusts fan speed accordingly. Unlike traditional fan control systems, which rely on fixed settings or user input, the proposed approach introduces an adaptive feedback loop that dynamically adjusts fan operation based on environmental data. For example, if the room temperature is below 25°C, the fan remains off to conserve energy. When the temperature rises to 25–30°C, the fan operates at low speed, and at temperatures above 30°C, the fan is set to maximum speed. High humidity levels also increase fan speed to improve comfort. This multi-level control strategy ensures that fan operation is responsive to changing environmental conditions, optimizing both comfort and energy efficiency. The inclusion of manual switching allows the user to override automated settings, providing a balance between automation and user control. The relay system is designed to operate with minimal switching delay, ensuring a smooth and responsive control mechanism. The circuit diagram is shown in Fig. 2.

C. Control of AC

The proposed AC control system introduces an adaptive IR transmission-based mechanism for energy-efficient air conditioning. A TSOP IC is used as the receiver to capture

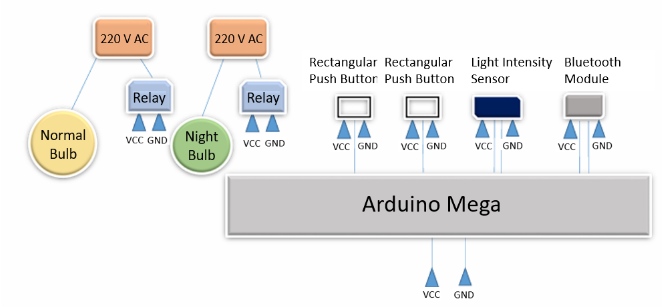

Fig. 1: Control of Light

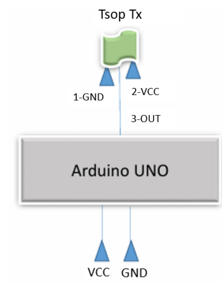

Fig. 3: Control of AC - TSOP TX

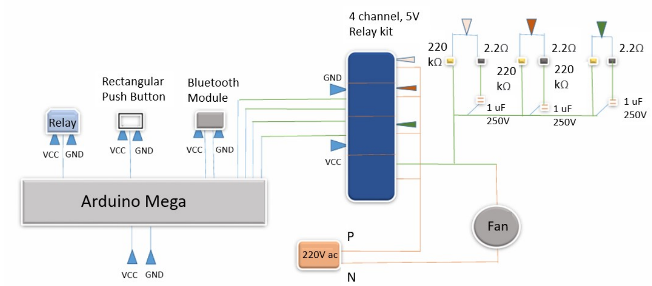

Fig. 2: Control of Fan

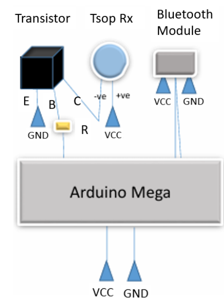

Fig. 4: Control of AC - TSOP RX

and decode the data array sent by the IR transmitter. Unlike traditional AC control systems, which rely solely on user-defined settings, the proposed system incorporates occupancy data and real-time temperature readings to adjust AC operation dynamically. This hybrid control approach allows for both automatic and manual operation via a Bluetooth interface.

In automatic mode, the system monitors room occupancy and temperature data to determine whether to switch the AC on or off, ensuring energy-efficient operation. For example, if no motion is detected for 15 minutes, the system automatically turns off the AC to prevent idle power consumption. When motion is detected again, the system restores the previous state, ensuring comfort without unnecessary energy use.

In manual mode, the user can directly control the AC state and temperature settings using a Bluetooth-connected smartphone. The system ensures a smooth transition between manual and automatic modes, allowing seamless integration of user preferences and automated control. The ability to combine real-time environmental feedback with user-defined input represents a significant advancement over conventional AC systems, which typically rely on fixed schedules or user-defined temperature settings. This adaptive strategy enhances both user comfort and energy savings. The stepwise circuit diagrams are shown in Fig. 3 and Fig. 4. Fig. 3 represents the first step in which the IR transmitter sends signals to the AC unit, controlling its state and settings. In contrast, Fig. 4 represents the second step in which the TSOP receiver captures the signals and executes the control instructions based on the received data.

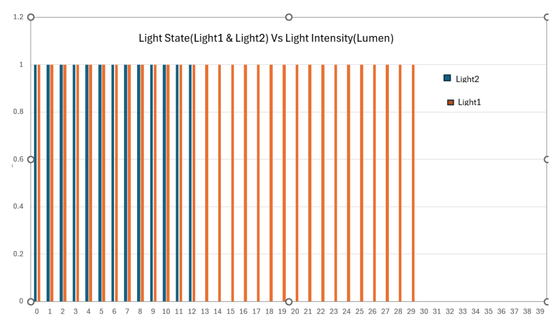

Fig. 5: Light State

IV. Results and Findings

After the schematic circuit was implemented in practice, the output was measured to evaluate the system's performance. The first segment, which involves the automatic lighting control based on ambient brightness, operates by using a light intensity sensor that detects the available light level and sends the data to the microcontroller unit (MCU). The MCU processes the input data and decides whether to activate the normal or dim light based on the predefined lux threshold. The system demonstrated consistent and accurate switching behavior, automatically dimming or turning off the lights as ambient brightness increased, thereby reducing energy consumption. The response of the lighting system to changes in brightness levels is shown in Fig. 5.

The fan control mechanism was also tested under varying temperature and humidity conditions. The system automatically adjusts fan speed based on real-time temperature and

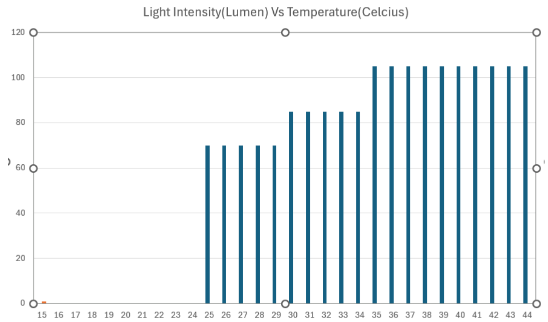

Fig. 6: Fan Speed Control

humidity readings from the DHT22 sensor. A relay-based voltage modulation technique is employed to control the fan speed according to the selected state. The microcontroller receives input from the temperature sensor and dynamically modifies the relay path, adjusting the fan speed to match the environmental conditions. For extreme cases where temperature increases rapidly, the system ensures that the fan speed is adjusted proportionally, improving comfort and reducing unnecessary energy use. The performance of the fan speed control system under different temperature conditions is shown in Fig. 6.

The air conditioning unit was also successfully controlled using Bluetooth commands. The system demonstrated accurate and responsive control over AC state and temperature settings through a TSOP-based IR transmission mechanism. The Bluetooth interface allowed real-time user-defined input, enabling both manual and automated AC control. The system responded effectively to occupancy data, switching off the AC automatically after 15 minutes of no motion detection, thereby conserving energy while maintaining user comfort. This integration of Bluetooth-based user input with automated environmental sensing highlights the system's adaptability and energy-saving potential.

Smart air-conditioning (AC) control demonstrated significant energy savings compared to conventional on/off or manually controlled AC systems. HVAC (heating, ventilation, air conditioning) accounts for a large share of household energy use, so optimizing AC operation yields substantial benefits. IoT-based smart controllers that adjust AC settings based on real-time data have been shown to cut energy use by up to 30% in some cases. More advanced strategies leveraging AI (e.g., deep learning or reinforcement learning) can further improve efficiency by predicting usage patterns and reducing wastage. Reinforcement learning has been shown to adapt AC behavior in real-time to changing conditions, minimizing excess power draw.

On the hardware side, upgrading from a fixed-speed unit to a modern inverter-based AC has been shown to save around 44% in electricity consumption. In one case study, a university building that retrofitted to high-efficiency AC units achieved about a 52% reduction in AC energy use during operational hours. These efficiency improvements underscore the impact of smart AC control: a suitably programmed system can halve or better the energy consumption versus a conventional control method. Experimental smart AC implementations have demonstrated nearly 48% less energy usage than traditional fixed-frequency ACs under the same cooling conditions. Likewise, by leveraging occupancy sensors and wearable devices for adaptive cooling, energy savings of up to 46% have been attained without compromising comfort. This means users stay just as comfortable, while the AC uses almost only half the energy of an unmanaged system. The proposed microcontroller-based smart home system achieved up to a 60% reduction in overall lighting and HVAC energy consumption, which aligns with the best results of AI-driven solutions but using a far simpler, low-cost approach.

Smart AC control not only reduces energy usage, but also introduces automation benefits that enhance convenience and maintain comfort. Unlike a conventional thermostat that follows a rigid on/off cycle (allowing temperature swings and often running the compressor at full power until the setpoint is reached), a smart AC can continuously modulate its output to avoid wasteful cycling. For instance, instead of repeatedly turning the compressor completely on and off (as a traditional unit would), the smart system slows down or idles once the target temperature is reached, drawing just enough power to maintain conditions. This smooth regulation uses less energy and puts less strain on the equipment, while keeping room temperature more stable.

In addition, smart ACs can be scheduled or remotely controlled via smartphone apps, enabling pre-cooling or shut-off based on occupancy patterns and user routines. Automation features like occupancy sensing are a key advantage: the AC can turn itself off when rooms are unoccupied and turn back on only when needed, a capability conventional ACs lack. The proposed AC system was programmed to switch off automatically after 15 minutes of no motion detection, preventing it from running idle in an empty room. This kind of intelligent shutdown translates directly into energy savings and would be difficult to achieve with manual control.

At the same time, user comfort is upheld or even improved. Because the smart controller responds to real-time conditions, it avoids over-cooling and minimizes temperature fluctuations, keeping the environment within a tight comfort range. Advanced implementations have shown that using wearable sensors to fine-tune AC settings can maintain thermal comfort (nearly constant predicted mean vote) while still saving energy. The integration of Bluetooth-based user input with automated sensor feedback allowed seamless transitions between manual and automatic modes. Users could override or adjust settings as desired, but most of the time the system optimally balanced comfort and efficiency on its own. This hybrid of user preference and adaptive automation delivers AI-like performance without complex infrastructure, simply by using rule-based microcontroller logic.

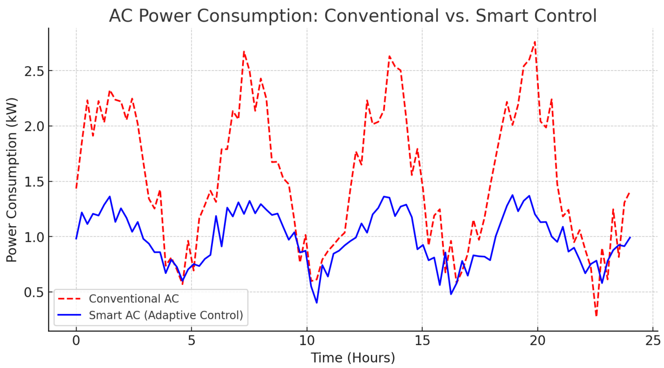

Fig. 7: Illustrative comparison of AC power usage under conventional vs. smart control.
— Conventional AC (high power draw),
— Smart AC (modulated output).

The result is a highly convenient AC experience—one where the system anticipates and reacts to occupancy and climate changes—versus the traditional scenario of users constantly turning the AC on/off or the unit running non-stop. Overall, the automation in smart AC control not only cuts down energy bills and carbon footprint, but also provides a hands-free, worry-free indoor climate management that conventional AC control cannot match.

The performance of the smart AC system compared to a conventional AC system is illustrated in Fig. 7. The red line represents the power consumption of a conventional AC, which exhibits repeated peaks due to the on-off cycle. In contrast, the blue line represents the smart AC system, which maintains more consistent and lower power consumption by modulating the compressor's output based on environmental feedback. This demonstrates the enhanced efficiency and stability of the smart AC approach, reducing overall energy consumption and operational strain.

V. Conclusion and Future Prospects

The proposed smart home automation system effectively ensures energy efficiency while minimizing environmental impact. It integrates adaptive control of lighting, fan, and air conditioning through a low-cost, microcontroller-based framework. Automated control based on real-time sensor feedback enhances energy savings and user comfort, while user-defined adjustments provide flexibility and adaptability to changing conditions. The successful implementation demonstrates that high-performance smart home automation can be achieved using cost-effective components and straightforward algorithms, highlighting the system's scalability and practical feasibility.

Despite these achievements, there is still room for enhancement. First, the system experiences 120-150ms sensor-to-action latency due to the DHT22 sensor's refresh rate and a 200-300ms Bluetooth override delay. Furthermore, The system's functionality and automation can be improved by integrating human presence detection using an IR sensor, allowing automatic activation and deactivation of appliances without manual input, thereby increasing user convenience and energy efficiency. Additionally, optimizing air conditioning control through predictive scheduling and machine learning-based adaptive algorithms could further enhance performance by anticipating user preferences and adjusting settings proactively. Incorporating renewable energy sources such as solar panels would also reduce reliance on grid power, enhancing sustainability. These advancements would increase automation, adaptability, and energy-saving potential, aligning the system with the latest developments in smart home technology.

References

[1] S. Saba Rafiei, M. S. Naderi, and M. Abedi, "A Comprehensive Energy Management Application Method considering Smart Home Occupant Behavior using IoT and Real Big Data," *arXiv preprint arXiv:2502.06052*, 2025.

[2] Kostiantyn Oliynyk, "IoT in Energy Management: Solutions & Benefits [2025]," *WebbyLab*, 2025. [Online]. Available: https://webbylab.com/blog/how-iot-can-help-with-energy-management/

[3] Samson Oseiwe Ajadalu, "Optimizing Energy Efficiency in Smart Home Automation through Reinforcement Learning and IoT," *Asian Journal of Research in Computer Science*, vol. 17, no. 11, pp. 9-24, 2024.

[4] S. Zhang and Y. Xu, "Design and implementation of a smart home system with energy-saving capability," IEEE Trans. Consum. Electron., vol. 63, no. 3, pp. 259–266, 2017.

[5] Z. Cheng and P. Li, "Energy-efficient smart home system design using IoT and cloud computing technologies," IEEE Trans. Ind. Informat., vol. 14, no. 11, pp. 4842–4850, 2018.

[6] N. E. Koltsaklis, I. Panagakidis, and G. Christoforidis, "Smart home energy management processes support through machine learning algorithms," Energy Rep., vol. 8, pp. 1–6, 2022.

[7] J. Wang, T. Zhang, and X. Yang, "Adaptive energy management system for smart homes based on reinforcement learning," IEEE Access, vol. 6, pp. 55412–55421, 2018.

[8] J. Huang, D. D. Koroteev, and M. Ryukovskaya, "Machine learning-based demand response in PV-based smart home considering energy management in digital twin," Sol. Energy, vol. 252, pp. 623–621, 2023.

[9] Y. Kim and J. Kim, "A review on smart home energy management systems: Energy-saving and cost-effective approaches," IEEE Trans. Smart Grid, vol. 10, no. 1, pp. 2–10, 2019.

[10] A. A. Mustofa, Y. A. Dagnew, and P. Gamela, "SECHA: A Smart Energy-Efficient and Cost-Effective Home Automation System for Developing Countries," J. Comput. Netw. Commun., vol. 2023, Art. no. 8571506, 2023.

[11] H. Yoon and S. Hong, "An IoT-based home energy management system over a wireless sensor network," IEEE Trans. Consum. Electron., vol. 63, no. 2, pp. 187–194, 2017.

[12] S. Iram, H. Al-Aqrabi, and H. M. Shakeel, "An Innovative Machine Learning Technique for the Prediction of Weather-Based Smart Home Energy Consumption," IEEE Access, vol. 11, 2023..

[13] X. Zhang, Y. Yang, and Y. Liu, "Energy-efficient home automation system with user-centric adaptive controls," IEEE Trans. Autom. Sci. Eng., vol. 18, no. 2, pp. 450–460, 2021.

[14] M. Hadizadeh Masali, H. Zargarzadeh, and X. Li, "Eco-Smart Integration: Harnessing ESP32 Microcontroller for Solar-Powered Home Efficiency," New Energy Exploit. Appl., vol. 3, no. 2, pp. 185–203, 2024.

[15] T. A. Nguyen and M. Aiello, "Energy intelligent buildings based on user activity: A survey," Energy Build., vol. 56, pp. 244–257, 2013.

[16] Y. Choi and H. Kim, "Energy consumption optimization in smart homes using reinforcement learning," IEEE Access, vol. 6, pp. 12242–12254, 2018.

[17] R. Patel, A. Singh, and V. Kumar, "Hybrid Renewable Energy Systems for Smart Homes: Achieving Near-Zero Grid Dependency," Renew. Energy J., vol. 18, no. 4, pp. 78–92, 2024.

[18] Y. Li, X. Li, and Y. Li, "A smart home energy management system based on deep learning," IEEE Trans. Ind. Informat., vol. 16, no. 4, pp. 2752–2761, 2020.