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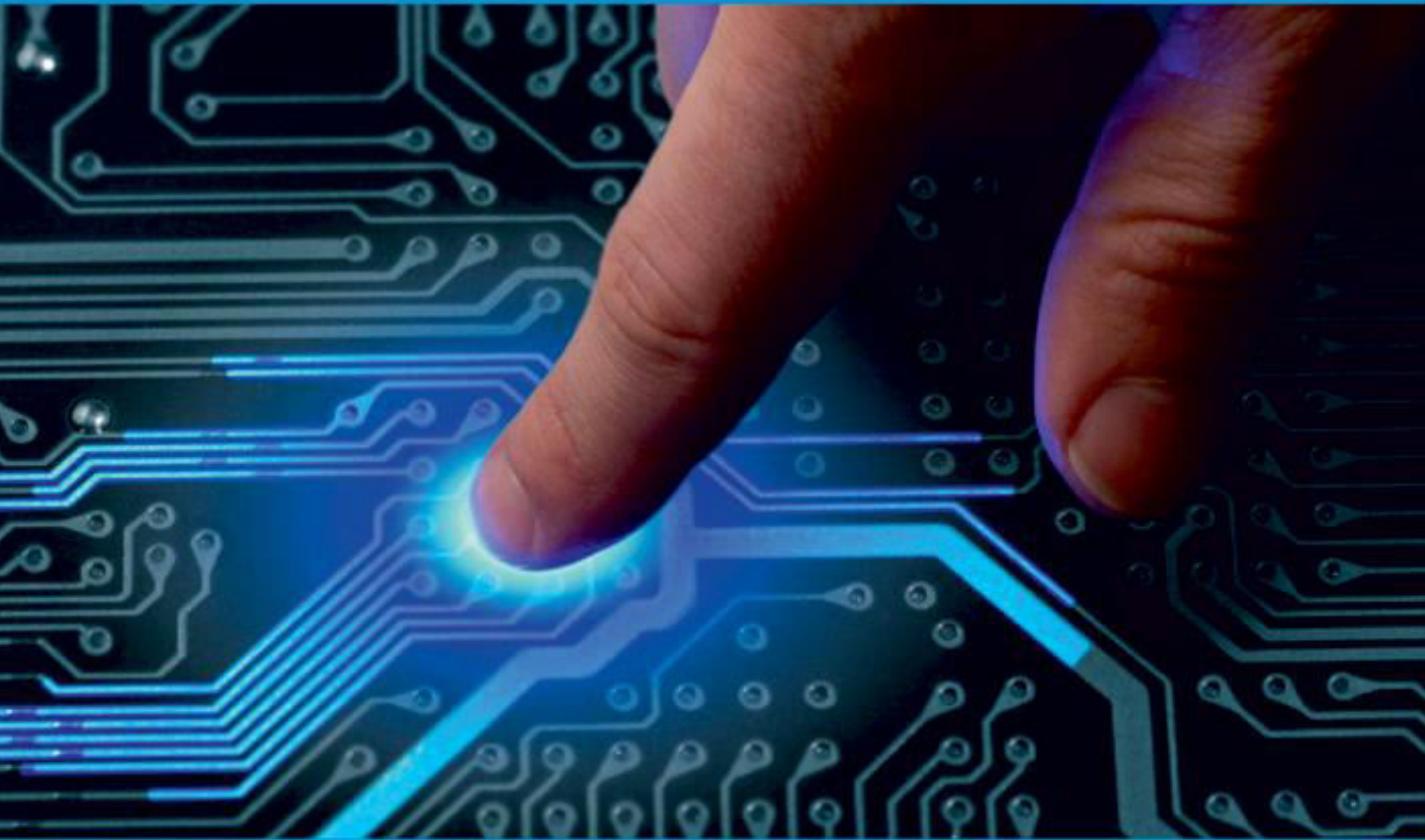

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Autonomous Smart Homes: Combining IoT, Energy Harvesting, and Security Solutions

Dr. P. Ravikumar, K. Atchyuta Valli, M. Deepika, K.Varahala Lakshmi, K. Shanmukha Sai Karthik, I. Pavani

Assistant Professor, Department of Electronics and Communication Engineering, GMR Institute of Technology, Rajam, A.P. India

Students, Department of Electronics and Communication Engineering, GMR Institute of Technology, Rajam, A.P. India

ABSTRACT: This paper explores the development of a safe, intelligent, and secure smart home automation system using integrated electronic devices, IoT, and Arduino technology. As the demand for IoT-based applications in smart buildings continues, managing energy consumption while ensuring the efficiency and reliability of devices is also becoming more challenging. This study examines various energy sources, including solar, thermal, mechanical, and radio frequency (RF), and shows how these technologies can be combined to provide sustainable energy sources for IoT, reduce grid dependency, and increase overall gender trust. It integrates a variety of sensors, including radio frequency identification (RFID), ultrasound, temperature, humidity, gas, and motion sensors, which send data to the Adafruit IO cloud server used with Yes That (IFTTT) for seamless access and management. This allows users to remotely monitor and control devices such as lights, heating, and security cameras from a smartphone or connected device, making it easy and convenient. Prioritize home security by taking care of it immediately. The system uses Arduino's open source platform to provide a highly scalable and cost-effective design that addresses issues such as security vulnerabilities, data limitations, and power reliability. By integrating heterogeneous energy harvesting with IoT and Arduino, this project delivers a powerful, autonomous, and adaptable smart home that redefines home automation by improving security, usability, and convenience, paving the way for the next generation of smart living.

KEYWORDS: Smart Home Automation, Internet of Things (IoT), Arduino, NodeMCU, Energy Harvesting, Sustainable Power Solutions, Heterogeneous Energy Sources, Home Security Systems, Environmental Monitoring, Remote Access Control, Energy Efficiency, Intrusion Detection, Fire and Gas Monitoring.

I. INTRODUCTION

The rapid advancement of communication technologies has revolutionized home automation, making smart homes a major application of the Internet of Things (IoT). These systems enable remote control and real-time monitoring of home appliances, thereby increasing comfort, convenience, safety and energy efficiency. By integrating sensors, actuators and controllers, modern smart homes have become an essential part of contemporary living and devices such as smartphones, televisions, washing machines and environmental sensors.

The advent of affordable microcontrollers was key to the proliferation of home automation systems. Earlier technologies such as Bluetooth, ZigBee, GSM and Wi-Fi offered limited functionality and range of communication. However, IoT-enabled systems have overcome these challenges by connecting devices through centralized platforms that enable features such as remote monitoring, centralized control, and energy optimization.

A typical IoT-based smart home system includes key components such as appliances, sensors (e.g. for temperature, humidity and motion), a central controller, data servers and user interfaces. Microcontrollers like NodeMCU with Wi-Fi capabilities play a key role in collecting data from sensors, executing user commands and facilitating communication with IoT servers. Programmable with tools like the Arduino IDE, these platforms effectively manage the smart home ecosystem.

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Advanced systems include mobile apps or web dashboards to seamlessly interact with IoT cloud platforms, analyze data from sensors and improve user experience. In addition, emerging technologies such as energy harvesting add an innovative aspect by converting energy from sources such as heat, motion and light into electricity. This reduces dependence on traditional energy networks, making smart homes more sustainable and environmentally friendly.

While these systems improve home management by improving security, access control, and energy efficiency, challenges such as managing multiple energy sources, optimizing storage, and reliable communications remain. Innovations like IoT Heterogeneous Energy Harvesting (IHEH) solve these problems by integrating multiple energy harvesting methods, providing consistent performance and ensuring system reliability.

By combining IoT technology, energy harvesting and automation, smart homes are evolving into robust, efficient and sustainable systems. These improvements not only address current limitations, but also pave the way for scalable and user-friendly solutions that enhance modern living.

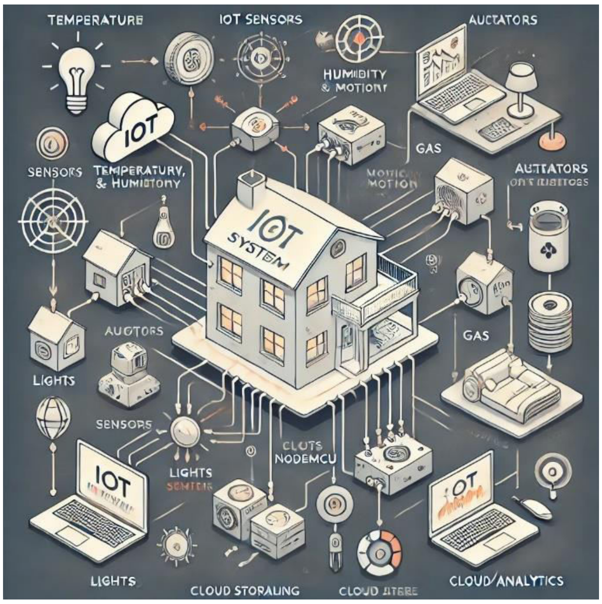

Fig 1: IoT based Home automation System

II. METHODOLOGY

1. Integrated Smart Home Automation System with Energy Harvesting and Advanced Automation Features

Smart home (SH) automation systems offer a range of benefits, such as ease of use, energy efficiency, convenience, comfort, security, entertainment, and peace of mind. Despite their advantages, many existing systems face challenges, including high costs, complex maintenance, limited functionality, and inadequate safety and security measures. Furthermore, they often lack user-friendly interfaces and robust IoT integration, while relying on short-range communication protocols like ZigBee, Bluetooth, or Wi-Fi, restricting their connectivity. These limitations make them inaccessible to a broader audience and less effective in addressing user needs comprehensively.

A. Proposed Hybrid IoT @HoMe Automation System

To address these challenges, a novel, cost-effective hybrid IoT at Home automation system is proposed, combining local and remote control capabilities. This system expands connectivity while providing a user-friendly interface accessible via smartphones or laptops, enabling effortless control of smart homes from any location. The proposed system emphasizes affordability, safety, and security by leveraging a NodeMCU controller and free mobile applications for real-time monitoring and control.

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Additionally, the system introduced an "Integrated Heterogeneous Energy Harvesting (IHEH)" framework, which enhances energy efficiency, sustainability, and user convenience through a layered architecture. This framework integrates energy harvesting technologies and IoT for optimized energy utilization and seamless automation

B. IHEH Framework Architecture

The IHEH framework comprises four layers:Energy Harvesting, Control and Sensing, Information Processing, and Application.

1. Energy Harvesting Layer (EHL):
This layer utilizes thermoelectric, piezoelectric, and light energy sources to harness ambient energy effectively.
It evaluates the characteristics of these energy sources for optimal energy harvesting and management in smart homes.
2. Control and Sensing Layer (CSL):
Sensors gather data on parameters such as energy usage, temperature, humidity, and motion for real-time control.
3. Information Processing Layer (IPL):
This layer collects and analyzes data from sensors and energy systems to detect patterns and predict energy demands.
Machine learning algorithms and data analytics extract actionable insights to enhance decision-making.
4. Application Layer (AL):
Provides user-friendly applications for managing household devices and energy systems.
Supports diverse domains like smart homes, agriculture, autonomous vehicles, and surveillance.

C. Automated Electricity Management: Electricity Dispatcher

The system incorporates an Electricity Dispatcher as the core controller for managing household electricity flow. It distinguishes between normal and emergency conditions based on voltage levels and automates processes accordingly.

1. Normal Situations: The automation system operates seamlessly, ensuring regular functioning of connected appliances within safe voltage limits.
2. Emergency Situations: Triggered when voltage levels deviate from the safe range, the system initiates protective measures to safeguard appliances.
Includes actions like shutting down at-risk devices and preparing for restoration once conditions stabilize.
3. Continuous Voltage Monitoring: Real-time monitoring identifies voltage irregularities and activates emergency protocols when necessary. A logical condition check determines the required actions, ensuring a swift response.
4. Automation Types: Local Automation: Hardware-based control independent of internet connectivity for reliable offline operation.
5. Web-Based Automation: Allows remote control of devices through a web interface.
5. App-Based Automation: Provides flexible appliance management via dedicated mobile or desktop applications.
6. Response Mechanisms: Shutdown Appliance: Protects devices by turning them off during emergencies.
7. Restoration Stage: Gradually reactivates appliances as voltage levels return to normal, ensuring a smooth transition back to standard operations.

Fig 2: Electricity Dispatcher

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The Energy Harvesting layer utilizes thermoelectric, piezoelectric, and light energy sources to power IoT-enabled systems, enabling efficient data gathering, processing, and utilization to enhance smart home efficiency, sustainability, and user convenience. The Application layer supports diverse domains, including smart homes, farming, self-driven cars, and surveillance, as illustrated in the system architecture diagram. Smart home (SH) automation systems offer numerous benefits, such as ease of use, energy efficiency, convenience, comfort, security, entertainment, and peace of mind. However, existing systems face challenges like high costs, maintenance difficulties, lack of IoT integration, user-friendly interfaces, limited functionality, inadequate safety measures, restricted wireless connectivity relying on short-range protocols like ZigBee, Bluetooth, or Wi-Fi, and insufficient installation knowledge. The proposed framework addresses these gaps, offering a block diagram that represents a system for managing household electricity dispatch under normal and emergency situations, automating voltage level checks, enabling appliance control via hardware, web, or app-based interfaces, and executing shutdown or restoration actions during emergencies.

2. *PRINCIPLE OF SMART HOME AUTOMATION*

The principle of this paper revolves around integrating energy harvesting technologies with IoT-based automation to create an efficient, cost-effective, and sustainable smart home system. By leveraging heterogeneous energy sources such as thermoelectric, piezoelectric, and solar energy, the system ensures reliable power for IoT devices, enabling continuous monitoring and control of home conditions. The framework incorporates advanced data processing, control mechanisms, and user-friendly interfaces to optimize energy utilization, enhance functionality, and improve the accessibility of smart home technologies. This holistic approach aims to address existing challenges in smart home systems, such as high costs, limited connectivity, inadequate safety measures, and restricted functionality, while promoting sustainability and user convenience.

3. *METHODS*

The methodology of this research begins with identifying key challenges in existing smart home (SH) systems, such as high implementation costs and non-user-friendly interfaces. The modeling phase involves selecting suitable materials and components to build the SH prototype, which is designed using NX10 software and constructed from plywood. The IoT @HoMe automation system is developed and implemented by wiring and connecting various components, including a bulb, fan, motor, and sensors, to the IoT @HoMe system, which integrates a NodeMCU, relay board, DC power source, and other components. The Piezoelectric Energy Harvesting (PEH) system is also implemented, consisting of a piezoelectric material (e.g., ceramic or polymer) connected to a rectifier circuit, voltage regulator, energy storage (e.g., capacitor or battery), and a load (e.g., LED or small devices). Coding is performed to program the microcontroller and achieve desired tasks. The design is reviewed to detect functional issues, and iterative testing ensures the system meets performance expectations. Enhancements and optimizations are carried out until the system demonstrates satisfactory operation. The finalized system incorporates a user-friendly smartphone app for convenient remote control and monitoring of home automation tasks.

4. *CIRCUIT DIAGRAM OF PIEZO ELECTRIC ENERGY*

The Piezoelectric Energy Harvesting (PEH) system harnesses mechanical stress or vibrations to generate electrical energy through piezoelectric materials like ceramics or polymers. The energy is converted into a stable output using rectification and voltage regulation, with surplus energy stored in capacitors or batteries for continuous use. Designed for adaptability, the system can be optimized for voltage or current output to suit various applications, from powering small devices to integrating with smart home systems. Rigorous testing and refinement ensure its efficiency and reliability, making it a sustainable solution for IoT-enabled technologies..Designed for efficiency, the system can be configured to optimize voltage or current output, making it suitable for small devices or integration into larger frameworks like smart homes. Through iterative testing and refinement, the PEH system offers a sustainable and reliable solution for powering IoT applications.

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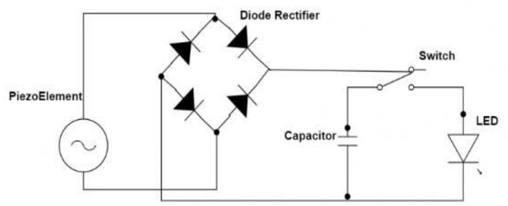

Fig 3: Piezo Electric Energy

5. *PIEZO ENERGY HARVESTING:*

The process of recovering energy from various sources, such as heat, vibrations, and light, is essential for enhancing energy efficiency and sustainability. This explores three primary methods of energy harvesting: thermal energy recovery, piezoelectric energy harvesting, and light energy harvesting.

Thermal Energy Recovery:

Thermal energy recovery involves capturing waste heat from machines and appliances, such as laptops, ovens, and air conditioners. The process typically includes several steps:

1. Heat Collection: High-load heat from devices is collected.
2. Conversion: This heat is fed into an AC-DC converter, which transforms thermal energy into electrical energy.
3. Storage: The generated electricity is stored in batteries for later use.

This method not only provides a reliable source of power but also extends the lifespan of the energy systems involved.

Piezoelectric Energy Harvesting:

Piezoelectric energy harvesters convert mechanical vibrations into electrical power. The process consists of the following stages:

1. Vibration Detection: Vibrations from sources like cookers or walking are detected.
2. Energy Conversion: The piezoelectric material generates an electric charge when subjected to mechanical stress.
3. Rectification: A full-wave rectifier converts the generated alternating current (AC) to direct current (DC).
4. Boosting and Storage: The DC power is boosted up and stored in a battery for use by microelectronic devices.

Piezoelectric harvesters are particularly advantageous due to their ability to provide higher power densities compared to other methods such as electrostatic transduction.

Light Energy Harvesting:

Light energy harvesting utilizes ambient light, often through small solar panels, to generate electricity. The process can be:

1. Energy Capture: Small indoor solar panels capture sunlight.
2. Conversion: The captured light is converted into DC power.
3. Storage: This power is then stored in batteries for later use.

This method is effective for extending the battery life of various devices and is commonly used in solar-powered sensor networks.

Intrusion Detection Systems:

In addition to energy harvesting techniques, the integration of smart systems enhances security measures in homes. Intrusion detection systems can utilize:

- Motion-based detection
- Vibration-based detection
- Image-based detection

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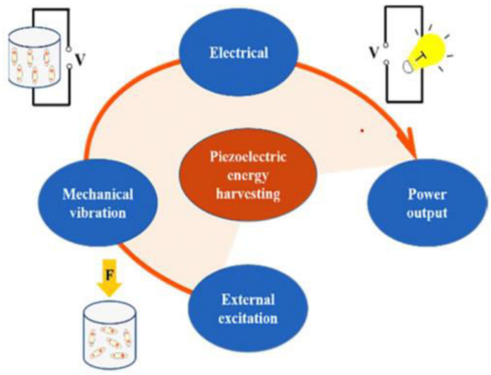

Fig 4: Piezo Energy Harvesting

III. RESULT

The IoT Home system integrates various home automation and monitoring functions to provide a seamless and user-friendly experience. This system manages home appliances such as lights, doors, fans and water pumps while monitoring environmental parameters such as temperature, humidity, gas level, water level and movement. Using technologies such as Adafruit IO, MQTT Dash and Google Assistant, IoT Home enables real-time remote control and monitoring via mobile devices and laptops. It uses NodeMCU microcontrollers for continuous connectivity and efficient operation.

1. Remote accessibility: Users can monitor and control devices and sensors from any location via the Internet. The system uses Adafruit IO and MQTT Dash for data visualization and real-time interaction.
2. Voice Commands: Integration with Google Assistant enables voice-activated control, making the system particularly beneficial for disabled or elderly users. Commands are passed through IFTTT to trigger device actions.
3. RFID Automation: The RFID card controls access to the main gate with a DC motor, increasing security and convenience.
4. Scalability: To address hardware limitations caused by multiple relays and sensors, the system uses two NodeMCUs – one for relay and sensor management and one for security components such as RFID and motion detection.
5. Energy Efficiency: Sensors like D6T MEMS monitor ambient conditions and trigger devices such as lights, fans and heaters based on human presence or temperature thresholds.

The system supports three methods of automation:

Local automation: Direct device activation based on data from sensors (e.g. lighting a light bulb when motion is detected or controlling appliances based on temperature thresholds).
Web-Based Automation: Commands transmitted via a web interface for remote device control.
App-Based Automation: Similar to web controls, commands are sent through a dedicated smartphone app interface.
The IoT Home system integrates several safety and security features:

1. Intrusion Detection: Use of motion, vibration and contact sensors (e.g. PIR and SW-420) to alert users of unauthorized access.
2. Fire Detection: Contains smoke-based sensors (e.g. MQ2) and temperature-based sensors (e.g. DHT11) to detect potential fire hazards.
3. Gas Detection: Monitors LPG leakage risks and reduces danger through early warnings.

The system GUI implemented in Adafruit IO and MQTT Dash is customizable and allows users to easily manage devices. Device status updates and sensor data are displayed in real time with the option to turn appliances on/off.
Improved accessibility: Voice control and remote access improve usability for all users, especially those with mobility issues.
Scalability and Flexibility: Multiple dashboards allow seamless integration with different devices and ensure scalability for future expansion.
Energy optimization: Smart sensors ensure that devices only work when needed, reducing energy waste.

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The IoT Home system paves the way for the integration of renewable energy and advanced storage technologies. Real-time energy management systems and IoT-enabled networks can further increase energy efficiency and sustainability. In addition, advances in heterogeneous energy harvesting could power IoT sensors, contributing to green solutions for the smart home.
This model demonstrates a reliable, cost-effective and scalable approach to smart home automation, offering users a variety of options while ensuring safety, accessibility and energy efficiency.

IV. CONCLUSION

This was advanced research and aligned sustainable and energy efficiency aspects of the smart home systems with cyber security and automation, which resulted in a broad framework. Therefore, the research emphasized and underlined the possibility for Arduino-based systems and IoT technologies to be applied toward modernizing living spaces into safe, intelligent, and ecologically conscious environments.

A particularly prime achievement is the creation of a secure, energy-efficient smart home system with elements such as wireless communication, self-energy harvesting, and strong cybersecurity measures. By acquiring sources for renewable thermal, piezoelectric, or even light energy, this system minimizes its dependency on external power supplies, reduces energy costs, and impacts the environment in a minimal way. This is not only an innovative form of energy harvesting that improves household energy management but also impacts the world's sustainability efforts through waste reduction and greener technologies.

From a security standpoint, encryption, secure device authentication, as well as intrusion detection, protect the privacy of users and prevent cyber-attacks. Such features ensure safety and reliability in home automation systems while keeping up with the growing cyber security challenges in IoT applications.

The versatility and scalability of these systems are also highlighted; they allow for the integration of more sophisticated sensors and actuators to support complex IoT ecosystems. The practical utility of such a system has been proven by the example of the IoT@HoMe framework, providing real-time monitoring and control of home appliances through interfaces as user-friendly as mobile apps or voice commands. Due to powering with solar energy and optimizing the hardware via printed circuit boards, the study is in tune with environmental goals and increases operational reliability.

Additionally, waste energy salvaged from the air conditioner using appliances and other ways shows potential to make it energy efficient and decrease the release of greenhouse gases into the atmosphere. This process saves money at the same time making an economic contribution and conserving the environment thereby creating a conducive environment for its wider adoption.

This paper will be used as a benchmark for future development of smart home systems. This is because the paper takes into consideration critical requirements in sustainability, cyber security, and user convenience. With these energies and security robustness in combination, the ground is laid out for next-generation self-sustaining and cyber-resilient smart homes made adaptive to users' needs. Advancements in modern living redefine connectedness, sustainability, and security for the future.

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