Journal of Intelligent Systems and Control
https://www.acadlore.com/journals/JISC

Integration of IoT for Smart Energy Management: Advancing Home Automation and Power Efficiency

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Received: 10-28-2024 **Revised:** 12-10-2024 **Accepted:** 12-21-2024

Citation: S. Mukhopadhyay, J. Gupta, and A. Kumar, "Integration of IoT for smart energy management: Advancing home automation and power efficiency," *J. Intell Syst. Control*, vol. 3, no. 4, pp. 227–238, 2024. https://doi.org/10.56578/jisc030403.

Abstract: The growing demand for energy, driven by urbanization and environmental concerns, has highlighted the need for innovative solutions in power management, particularly within residential and small business settings. This study presents a comprehensive smart home automation system, which is based on Internet of Things (IoT), designed to address these challenges. By integrating a smartphone application with Arduino-based hardware, the proposed system enables real-time remote operation, scheduling, and monitoring of electrical appliances. Bluetooth connectivity, coupled with advanced coding techniques, was employed to accurately measure power consumption and compute associated costs. The system's user interface was evaluated for its ease of use, responsiveness, and high accuracy, providing users with the ability to track energy usage trends, optimize appliance operation, and make informed decisions regarding energy consumption and cost management. Furthermore, the solution promotes sustainable energy practices by facilitating the reduction of unnecessary energy consumption. This scalable, cost-effective approach is poised to support the broader adoption of energy-efficient technologies. Future enhancements, such as integration with voice assistants and the addition of Wi-Fi connectivity, are expected to further expand the system's capabilities. The findings demonstrate the significant potential of IoT technologies to transform energy management and foster environmentally conscious behavior in smart homes.

Keywords: Energy monitoring; Power management; Smart home automation; Internet of Things (IoT); Arduino microcontroller; Bluetooth communication; Remote appliance control; Sustainable energy practices

1 Introduction

In the 21st century, the notion of smart homes has gained substantial support as a solution to the issues provided by urbanization, increased energy needs, and the environmental effect of excessive energy usage. The IoT [1] has evolved as a game-changing technology, allowing objects and systems to communicate with one another to create new solutions across several disciplines. One major use of IoT is home automation and energy management, where smart technology may help to optimize energy consumption while also improving consumer ease. This study takes a step toward in fulfilling this ambition by combining IoT to produce intelligent, cost-effective solutions for monitoring and regulating power use.

The fast development of urban populations, along with an increased reliance on electricity, has resulted in rising energy demands, taxing current power production facilities and driving up electricity bills. Furthermore, inefficient energy usage and waste in the residential and commercial sectors contribute to the depletion of natural resources and environmental damage. The rising urbanization and increased energy consumption have resulted in substantial issues in energy management. For instance, global electricity consumption [2] has been expanding at an average rate of 3% yearly since 2010, with residential energy use accounting for around 29% of total electricity consumption worldwide. Poor energy usage in households adds to roughly 20% of energy wastage, as indicated by the International Energy Agency (IEA). This wasting not only increases electricity prices but also exacerbates environmental challenges, such as greenhouse gas emissions. These difficulties underline the urgent need for creative solutions like IoT-based smart home automation systems, which can minimize energy use and promote sustainable practices.

These difficulties highlight the need for novel approaches to promoting energy saving and sustainable development. Smart energy management systems [3] based on IoT have emerged as a viable option. Such systems provide real-time monitoring, automation, and optimization of energy usage, allowing customers to make educated decisions regarding their electricity consumption. They also help to integrate renewable energy sources, resulting in a cleaner and more sustainable energy ecology. The impetus for this project derives from the urgent need to solve these difficulties while also offering end consumers with inexpensive and user-friendly solutions for successfully managing their energy use.

The proliferation of IoT devices [4], as well as developments in communication technology, have enabled the design and implementation of systems that were previously deemed technically and economically infeasible. Using these technical breakthroughs, the suggested solution aims to close the gap between energy efficiency and cost-effectiveness, making smart energy management more accessible to a larger audience. The initiative focuses on solving the concerns of homes and small business owners, who frequently face high power bills and little access into their energy usage habits.

Despite the developments in IoT-based home automation systems, some gaps remain unresolved. Many present systems focus exclusively on basic automation tasks without integrating complete energy management features. For instance, while some systems have remote control capabilities, they generally lack real-time energy consumption tracking and cost analysis, which are critical for informed decision-making. Additionally, many solutions are not developed with scalability in mind, restricting their usability in different residential and small company situations. This study intends to overcome these gaps by designing a cost-effective, user-friendly IoT-based system that integrates real-time monitoring, remote control, and energy optimization capabilities.

The major goal of this study is to create an IoT-based home automation and energy monitoring system that takes a complete, user-centric approach to regulating power use. The system is intended to accomplish the following particular goals:

• Real-time monitoring: This allows customers to track their energy use and gain extensive insights into the usage patterns of particular appliances.

• Cost calculation: This provides realistic estimates of power prices, allowing customers to comprehend the financial consequences of their energy use and find cost-saving alternatives.

• Remote operation: This allows consumers to remotely operate their electrical appliances via a mobile app, increasing ease and aiding proactive energy management.

• Energy optimization: This enables consumers to optimize their energy use by scheduling appliance use and obtaining advice for energy-saving measures.

• Scalability and affordability: This makes sure that the system is scalable to suit a variety of use cases while being cost-effective for mass adoption by individuals and small companies.

The scope of the research goes beyond the technical installation of the system to include an assessment of its efficacy in terms of energy savings and user satisfaction. The study's goal is to illustrate the potential of smart technologies in revolutionizing how energy is consumed and managed at the grassroots level by combining IoT and home automation.

Smart energy management is critical for tackling global energy concerns. With the world's population anticipated to reach 9.7 billion by 2050, demand for energy is likely to skyrocket, demanding novel solutions to balance supply and demand while minimizing environmental effect. Traditional energy management approaches, which rely on human monitoring and control, are unsuitable to address these difficulties because of their limited scalability and efficiency.

The integration of IoT into energy management systems has various benefits that make it a game changer in this industry.

• Enhanced energy efficiency: Smart energy management systems provide granular control and monitoring of energy consumption, assisting users in identifying and eliminating inefficiencies.

• Cost savings: By offering insights into energy use trends and enabling automatic appliance control, these solutions help consumers drastically cut their power expenditures.

• Environmental benefits: Efficient energy consumption minimizes the need for fossil fuel-based power generation, resulting in reduced greenhouse gas emissions and a smaller carbon footprint.

• User empowerment: By providing real-time data and actionable insights, smart energy management systems enable users to regulate their energy use and make educated decisions.

• Support for renewable energy: Smart systems may effortlessly interact with renewable energy sources like solar panels, allowing consumers to increase their reliance on sustainable energy.

The proposed method corresponds with these advantages, offering a practical and meaningful answer to the issues of energy management. By focusing on households and small business owners, the system serves a vital section of energy users who are generally hesitant to embrace modern energy management technology owing to cost or complexity. This study seeks to provide a holistic system that integrates IoT capabilities, real-time data processing, and automation to provide a consistent user experience.

The remaining sections of this work are structured below. Section 2 examines present research and technology on IoT-based home automation and energy management systems, identifying important gaps and potential. Section 3 describes in full the design and implementation process, including the selection of hardware and software components. Section 4 provides an in-depth description of the proposed system's design, components, and capabilities. The system's performance in attaining its objectives was given and assessed, with experimental data supporting the findings. Section 5 discusses the limitations of this study. Finally, Section 6 highlights the study's main contributions and offers insights into the consequences of the findings, problems faced, and prospective routes for future research and development. The study's organized approach seeks to offer a full description of the research project's implementation and prospective influence on energy management practices.

2 Literature Review

Khalil and El Shenawy [5] described an IoT-based smart home automation and energy monitoring system designed for effective power management in residential and small commercial environments. The system combines Arduino-based hardware with a mobile application to provide real-time monitoring, remote control, and scheduling of electrical appliances. It allows for precise power usage tracking and cost computation through the use of Bluetooth connectivity and innovative coding techniques. Performance metrics demonstrate its great accuracy, quickness, and user-friendly interface. Future upgrades, such as Wi-Fi connectivity and voice assistant integration, offer further capability. The suggested system provides a scalable, cost-effective solution for optimizing energy use and encouraging sustainable energy habits. Stolojescu-Crisan et al. [6] proposed the qToggle system, an IoT-based smart home automation solution. It uses a flexible Application Programming Interface (API) to link sensors and actuators, especially with ESP8266/ESP8285 chips and Raspberry Pi boards. The system's user-friendly smartphone application enables a variety of home automation activities, including lighting, temperature control, and energy monitoring. qToggle stresses simplicity and versatility, allowing for easy device connection and administration. It also promotes solar energy integration, which improves energy efficiency. While the system is solid, it concentrates on current technology without considering the cost-effectiveness of mass adoption.

Ali et al. [7] investigated an IoT-based home automation system utilizing Arduino and ThingSpeak. The system combines a variety of sensors and devices to automate critical house tasks, including lighting, fan control, and environmental monitoring. It leverages the Message Queuing Telemetry Transport (MQTT) protocol for fast Local Area Network (LAN) connectivity and the ThingSpeak cloud platform for data processing and display. The system is intended to be cost-effective, with an emphasis on reducing power usage and increasing the longevity of digital equipment. While the system provides real-time information and control through a mobile application, it focuses on simple automation activities rather than complex energy management tactics. Alturki et al. [8] investigated a smart home automation system that combines IoT and blockchain technology. It stresses the use of low-cost, scalable components and a security-focused design to combat cyber attacks. The system includes GSM modules for remote control and uses Raspberry Pi and Arduino for device administration. It has an easy-to-use interface and drag-and-drop capabilities for customizing the house arrangement. The study emphasizes the significance of secure communication and authentication, utilizing blockchain to improve security. While the system provides strong protection and flexibility, it focuses exclusively on security without fully addressing cost-effectiveness and energy management issues.

Alani et al. [9] examined two IoT network systems for smart home automation, NETPI and BLYNK. It demonstrates NETPI's versatility in handling many NodeMCU controllers inside a single framework, resulting in strong monitoring and management of household appliances. While BLYNK is easy to use, its single- controller architecture and increased energy costs restrict its potential. The study underlines the need for dependable, cost-effective solutions in areas with unreliable electricity, such as Iraq. It addresses issues such as water distribution and power use in order to improve quality of life through more automation. However, the emphasis remains on network platform capabilities rather than overall energy management solutions. Taiwo et al. [10] described an IoT-based intelligent smart home control system that uses machine learning to improve security. The system controls and monitors home appliances and ambient elements via an Android mobile application, using a support vector machine (SVM) algorithm to distinguish between typical inhabitants and intruders, hence decreasing false alerts. The system was developed with an ESP8266 board, an ESP32-CAM, and a variety of sensors to provide a complete home automation solution. This method prioritizes security and intelligent decision-making, distinguishing it from other systems that rely solely on basic automation and controls. Begum et al. [11] showed how to build an IoT-based home automation system with Raspberry Pi 3 and voice commands. The technology is intended to aid the elderly and disabled by allowing them to operate household appliances using voice commands via a mobile app. It connects devices via Wi-Fi and monitors power use with current sensors. The solution incorporates Blynk and IFTTT for smooth operation and offers a user-friendly interface for remote administration. While the technology improves accessibility and convenience, it is primarily concerned with voice control and does not address energy management or cost-effectiveness for wider adoption.

Islam et al. [12] provided an IoT-based home automation framework that makes use of NodeMCU and the MQTT protocol. The solution enables customers to remotely monitor and manage household appliances via a mobile application. It has sensors for temperature, humidity, and gas detection, which provide real-time data and improve home safety and convenience. The framework prioritizes cheap cost and user-friendliness, including open-source firmware enabling simple installation. While the system adequately regulates environmental factors and appliance control, it is primarily concerned with basic automation and lacks advanced energy management capabilities. Khan et al. [13] demonstrated an IoT-based energy management system for smart homes that use the ESP8266 controller and Wi-Fi technology. The system monitors and manages electrical loads, delivering real-time information on voltage, current, and power usage. It uses a web-server-based technique for online viewing and control, allowing customers to operate appliances remotely from a mobile app. The study underlines the need of optimal energy consumption in reducing financial losses in power systems. While the system provides strong monitoring and control capabilities, it concentrates on fundamental energy management rather than sophisticated optimization techniques or cost-effectiveness for wider deployment.

Recent improvements in IoT-based energy management systems emphasize its potential to increase energy efficiency. Sheela et al. [14] designed a smart energy meter utilizing the ESP32, enabling users to track and regulate energy use via a mobile app. Esquicha-Tejada and Copa-Pineda [15] demonstrated that IoT automation might save power usage by 30% yearly. Dahir et al. [16] coupled machine learning with IoT to optimize energy usage in Somalia using real-time data analytics. Al-Shareeda et al. [17] studied long-range IoT technologies, concentrating on enhancing communication for energy management applications, underlining the need of novel solutions.

Latest research stress the integration of IoT in boosting energy efficiency and waste management in smart homes. Ehsanifar et al. [18] emphasized the remarkable energy cost reductions feasible using IoT technology, while de Oliveira Cavalcanti and Pimenta [19] proposed a conceptual framework for electric energy management that consolidates many elements impacting consumption. Zaman et al. [20] further investigated IoT's involvement in smart city programs, addressing issues and giving insights for sustainable urban management. These contributions underline the need for comprehensive, user-friendly solutions that promote energy efficiency and accessibility.

2.1 Novelty

This study stands out because it focuses on a low-cost, scalable IoT-based system designed exclusively for energy management and monitoring. Unlike previous research, which primarily focus on certain functionality or rely on expensive, sophisticated current technologies, this study combines Arduino-based hardware with Bluetooth connection to provide real-time power usage insights and remote control capabilities. The system's design emphasizes cost and accessibility, making it ideal for homeowners and small companies looking for realistic energy management solutions. A crucial innovation is the introduction of a user-friendly mobile application that allows for smooth interaction with the system. By addressing high implementation costs and operational complexity, which are frequent drawbacks in previous systems, this system assures accessibility and efficacy for a larger audience. Furthermore, the modular architecture allows for future scaling, enabling integration with cutting-edge technologies like Wi-Fi networking and smart grids.

This holistic method closes the gap between cost and sophisticated functionality, providing a fresh viewpoint on IoT-based energy management systems that prioritize both user experience and sustainable energy practices. The suggested system's combination of real-time monitoring, cost-effectiveness, and ease of use makes an important addition to the field of smart home automation and energy saving.

3 Methodology

The suggested system's technique involves integrating Arduino-based electronics with Bluetooth connectivity and relay modules to develop a functioning prototype for real-time power consumption monitoring and management of electrical equipment. This method prioritizes simplicity, cost-effectiveness, and practicality for proof-of-concept testing, laying the groundwork for future scaling in home or small company settings. The system is intended to measure and regulate power use by carefully coordinating its hardware and software components. The fundamental hardware platform is an Arduino microcontroller, which was chosen for its versatility, low cost, and interoperability with a broad variety of sensors and modules. The Arduino is the central processing unit, which manages sensor inputs and executes control orders.

To promote communication and user engagement, the system includes a Bluetooth module, which allows for seamless wireless connectivity between the Arduino and a mobile app. This arrangement enables users to monitor real-time power use and remotely operate electrical equipment using their cellphones. Bluetooth connection simplifies implementation and eliminates the need for complicated networking infrastructure, making the technology available to a larger audience.

The relay module serves as a bridge between the Arduino and the connected electrical appliances, allowing the system to turn gadgets on and off depending on user inputs or predetermined schedules. The relays were programmatically controlled, guaranteeing that the system can manage a wide range of loads and appliance kinds.

The Arduino was programmed to do a number of critical functions. It detects app input, such as user orders to turn on or off equipment. It then appropriately regulates the relay module, ensuring accurate administration of the associated devices. Furthermore, the Arduino evaluates power consumption in real time, giving customers with useful information about their energy usage. Figure 1 depicts a diagrammatic depiction of the technique, including the interaction of the system's fundamental components as well as the flow of data and control signals. This systematic approach emphasizes the usefulness and promise of IoT technology in developing smart energy management systems.

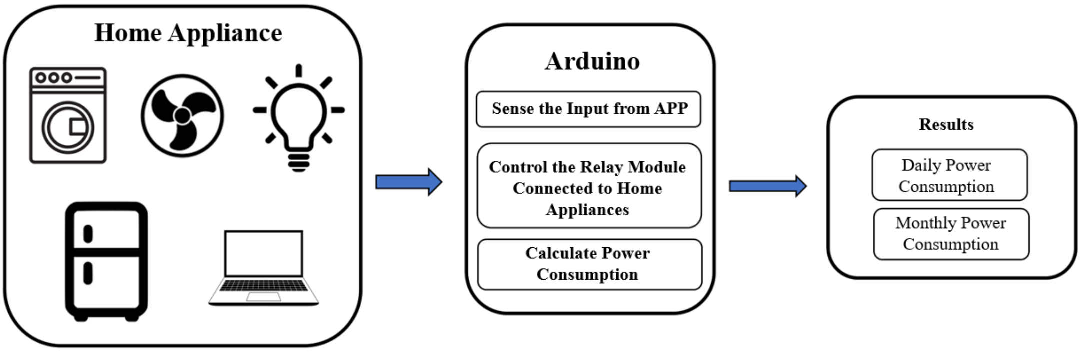

Figure 1. Methodology

The outcomes of this procedure are presented in the form of daily and monthly power usage data. This information is critical for consumers to make educated decisions regarding their power use, resulting in cost savings and more effective energy management. The system's design stresses usability and accessibility, making it a viable answer to current energy concerns. While the current implementation is intended as a proof of concept, the system's architecture is flexible to changes necessary for full-scale deployment in a home environment. For example, Wi-Fi connectivity and integration with sophisticated sensors for energy metering and load balancing may be required for widespread application.

4 Results

4.1 Hardware Implementation

The hardware implementation of the IoT-based energy monitoring and control system focuses on integrating Arduino microcontrollers, relays, and electrical appliances to produce a reliable and functional configuration. This configuration allows for exact control and monitoring of power use, resulting in maximum performance and energy efficiency. The careful selection and connectivity of hardware components lay the groundwork for the system's stability and scalability.

The circuit diagram in Figure 2 depicts the hardware components utilized in the proposed IoT-based home automation system. At its heart lies an Arduino Uno, which acts as the primary controller. It is linked to an HC-05 Bluetooth module, which allows wireless connectivity for remote control. The system contains a 2-channel relay module (SRD-05VDC-SL-C) that manages high-power devices and allows the Arduino to securely operate them. The relays are linked to light-emitting diodes (LEDs) that symbolize appliances in this configuration. For demonstration reasons, a 9V battery is depicted as the power source, while the real experiment is powered by a main power supply. This setup focuses on the integration of Bluetooth connectivity and relay control for optimal home automation.

At the heart of the hardware configuration are Arduino microcontrollers, which act as central processing units. Arduino boards were selected because they are versatile, inexpensive, and simple to program. These microcontrollers are in charge of processing sensor data and carrying out control orders received through the mobile application. The modular architecture of Arduino boards enables smooth connection with other hardware components, making them perfect for IoT applications. The Arduino microcontrollers communicate with current and voltage sensors to properly assess power usage. The data acquired by these sensors was analyzed in real time and sent to the associated mobile app via Bluetooth connection. The microcontroller's processing efficiency guarantees low latency, allowing for quick replies to user inputs.

Relays are important in the hardware configuration because they act as an interface between the Arduino and the electrical appliances it is linked to. These electromechanical switches regulate the flow of energy to devices, allowing them to be turned on and off remotely in response to human inputs or predetermined schedules. The usage of relays guarantees that the system can manage a variety of electrical loads while being safe and reliable. Each relay was carefully chosen based on its power rating to guarantee compatibility with the appliances it powers. The system is intended to support both low-power devices, such as lighting fixtures, and high-power appliances, such as air conditioners and refrigerators. The relays are linked to the Arduino via digital output pins, which give the required control signals. When the microcontroller provides a signal, the relay activates or deactivates the electrical circuit, therefore controlling the linked device.

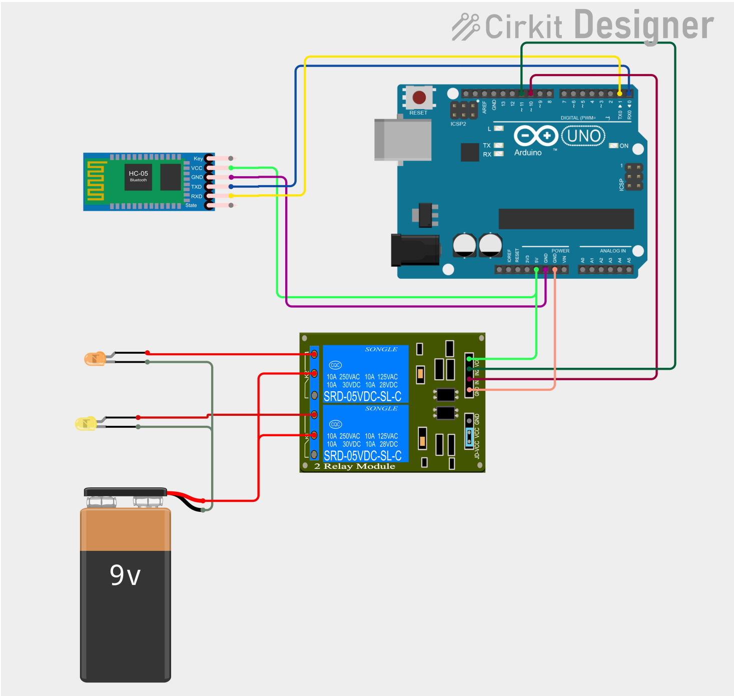

Figure 2. Circuit diagram

The system is intended to monitor and control a wide range of electrical equipment usually found in household and small business environments. These appliances are connected to the relays, allowing for centralized control via the mobile application. Appliances are connected with careful consideration of their power ratings to avoid overloading and guarantee system stability. Proper wiring and insulation were used to improve safety and reduce the likelihood of electrical dangers. The hardware arrangement was tested under a variety of stress circumstances to ensure its performance and longevity. This intensive testing assures that the system can function reliably for an extended duration.

During the hardware implementation phase, no major obstacles were encountered, as the system was built with simplicity and adaptability in mind. However, small challenges developed during the integration of the software with the hardware components, notably in creating continuous communication between the Arduino microcontroller and the Bluetooth module. Initial attempts to synchronize the data flow between the mobile application and the hardware resulted in intermittent delays or missed commands. This issue was fixed by fine-tuning the baud rate settings and ensuring appropriate startup of the Bluetooth module in the Arduino code. Additionally, rigorous debugging and testing of the relay module connections were necessary to assure proper switching of appliances without electrical interference. These small issues were overcome through repeated testing and optimization, resulting in a robust and responsive system.

The combination of Arduino microcontrollers, relays, and electrical appliances creates a unified system capable of real-time monitoring and control. The hardware's modular architecture facilitates scalability, allowing the system to incorporate more devices or sophisticated functions such as load balancing or integration with renewable energy sources. Future hardware upgrades might include the replacement of Bluetooth modules with Wi-Fi or Zigbee communication modules, which provide longer range and better connection. The addition of energy meters and smart sensors might improve the system's capacity to give precise information about energy use trends.

The hardware implementation of the IoT-based energy management system shows a feasible and effective method for real-time power usage monitoring and device control. The system uses Arduino microcontrollers and relays to give a low-cost option for smart home automation. The meticulous consideration of component selection, connection, and safety guarantees that the system is both functional and adaptable to future developments.

Figure 3 depicts the hardware configuration for the home automation and energy monitoring system using IoT, which demonstrates the integration of critical components for real-time power consumption monitoring and control of electrical equipment. The Arduino microcontroller acts as the central processing unit, taking orders from a mobile application and controlling connected appliances. A relay module connected to the Arduino acts as a switch, controlling the power supply to devices like LED lamps, which represent home appliances in this configuration. A power sensor monitors energy use and transmits it to the Arduino for real-time tracking. The Bluetooth module facilitates communication between the mobile app and the Arduino, allowing for remote control and feedback. The breadboard and cabling serve as connection prototypes, while a dedicated power source ensures that all components work together seamlessly, showcasing an efficient IoT-based solution for home automation.

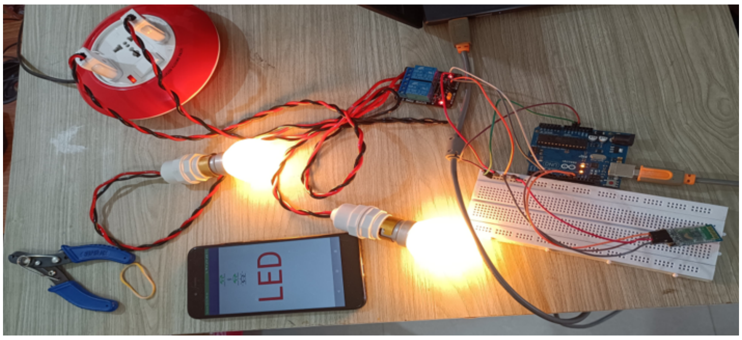

Figure 3. Hardware implementation

4.2 Software Implementation

The software implementation of the IoT-based energy monitoring and control system is intended to provide seamless connectivity, efficient energy monitoring, and real-time control of electrical appliances. The software was created with the Arduino IDE, utilizing libraries and programming approaches to provide reliable operation and user-friendly interaction via a mobile application.

The Arduino Integrated Development Environment (IDE) was used to program the Arduino microcontrollers, providing a simple platform for creating, compiling, and uploading code. The IDE supports a variety of libraries, including the SoftwareSerial library, which is essential for establishing Bluetooth connectivity between the Arduino board and the mobile application. The SoftwareSerial library was used to enable serial communication via non-default pins, allowing the Bluetooth module to work with other peripherals attached to the microcontroller. This library enables the seamless transmission of data, ensuring that real-time monitoring and control actions occur without delay.

Calculating power usage for each connected appliance is an important part of the software solution. This is accomplished by assigning a variable that maintains each appliance's power rating. When an appliance is turned on using the mobile application, the software sets up a counter to measure how long the equipment is operational. The counter records time in predetermined units, such as hours, allowing for exact tracking of usage. The power usage is then computed using the formula in Eq. (1),
where,

- P: Power rating in watts (W)
- t: Time in hours (h) over which power was consumed
- E: Energy consumption in joules (J) or kilowatt-hours (kWh)

This data is further processed to compute the corresponding cost based on the electricity tariff rate, providing users with detailed billing information.

$$E = \frac{P \cdot t}{1000} \tag{1}$$

To improve performance and efficiency, the program uses a variety of clever coding approaches. For example, event-driven programming reduces resource usage by ensuring that the microcontroller only handles relevant events, such as changes in appliance status or user commands. Additionally, data structures such as arrays and hash tables were used to record appliance information, including power ratings and status. These structures allow for efficient data retrieval and updating, which reduces computing overhead. The program also includes error-checking techniques to assure data integrity during Bluetooth communications.

The Arduino microcontroller, Bluetooth module, and relays work together to seamlessly integrate software and hardware components. The program controls the relays by delivering digital signals to the Arduino's appropriate pins. When a command is received from the mobile app, the program validates it, changes the appliance state, and activates or deactivates the relevant relay. The system is intended to manage several appliances at once, providing scalability and dependability. The program also logs historical data about power use, which users may use to make long-term decisions and analyses.

The software's focus on giving actionable insights enables customers to make educated decisions regarding their electricity consumption. By displaying energy usage trends and related costs, users may discover inefficient appliances or behaviors and take remedial action. The integration of services like scheduling and alerts improves user convenience and engagement.

The software implementation is the foundation of the IoT-based energy monitoring and control system, converting hardware inputs into useful insights and actionable results. Using the Arduino IDE, SoftwareSerial library, and innovative programming approaches, the software offers real-time monitoring, precise power consumption computation, and easy control via a mobile application. This complete approach guarantees that the system is both practical and adaptive, opening the way for increased energy efficiency and cost savings in smart home settings.

The software implementation of the IoT-based energy monitoring and control system is intended to provide seamless connectivity, efficient energy monitoring, and real-time control of electrical appliances. The software was created with the Arduino IDE, utilizing libraries and programming approaches to provide reliable operation and user-friendly interaction via a mobile application.

Algorithm 1 IoT-Based Power Consumption Monitoring and Control

Input: Bluetooth input for control commands.
Output: Power consumption and cost for each device.
Initialize Components:
Set up the software serial communication on pins 11 and 12; define constants for relays, power ratings, and unit charge; initialize variables for device start times and consumption.
Setup Function:
Configure relay pins as outputs; set initial states for relays to HIGH (off); begin serial communication at 9600 baud rate.
Main Loop:
while $true$ **do**
if $Bluetooth\, data\, is\, available$ **then**
Read the incoming value and process it.
Process Bluetooth Input:
switch $Received\, value$ **do**
case *1* **do**
Turn on relay1 and record the start time.
case *2* **do**
Turn off relay1 and calculate power consumption for device1.
case *3* **do**
Turn on relay2 and record the start time.
case *4* **do**
Turn off relay2 and calculate power consumption for device2.
Calculate Power Consumption:
Calculate the time in hours between start and end times; multiply the time by the power rating to get consumption.

Update Power Consumption:
Calculate costs for each device based on consumption and unit charge; print the consumption and cost for each device to the serial monitor; delay for six seconds before repeating the loop.

The method began by establishing the appropriate hardware and software setups, such as serial connectivity and relay control. The main loop listened for Bluetooth instructions that indicate whether a device should be switched on or off. When a gadget was turned on, the system recorded its start time. When it received an order to switch off a device, it estimated the power consumption based on the device's operating time and power rating. The cost was then calculated based on this usage and shown to the consumer. The procedure guarantees that energy usage is efficiently monitored and controlled, with real-time feedback on power consumption and prices.

4.3 Smart Energy Management Capabilities

The system successfully integrates hardware and software components to create a unified platform for real-time monitoring and management of electrical appliances. The Arduino microcontroller acts as the central hub, processing sensor inputs and executing commands sent via the Bluetooth communication module. The accompanying software provides exact calculations and rapid response, allowing users to monitor power use and operate equipment remotely. The system's key features include real-time monitoring, which allows it to gather and show statistics on power use, giving customers precise insights into the energy usage of particular appliances. Furthermore, the inclusion of

Bluetooth connectivity allows for remote control via a mobile application, allowing users to turn appliances on and off, schedule operations, and monitor consumption trends from anywhere. The system also provides real-time billing information by calculating and showing power bills depending on use, allowing users to track their spending more effectively.

These functionalities were rigorously tested and validated during the implementation phase, ensuring the system operates reliably across diverse scenarios. Quantitative metrics were collected to evaluate the system's performance in terms of accuracy and responsiveness.

Table 1 shows the power rating, usage time, and power consumed for two appliances across five days, where Appliance A is a LED light of 5W and Appliance B is a fan of 7W. The cost is not included in the table as the rate of electric consumption varies from place to place and the rate can be multiplied with the power consumed to get the approximate cost of the consumption.

Table 1. Power consumption of appliances across five days

Day	Appliance	Power Rating (W)	Usage Time (hrs)	Power Consumed (Wh)
Day 1	Appliance A	5	5	25
Day 2	Appliance A	5	6	30
Day 3	Appliance A	5	4	20
Day 4	Appliance A	5	5	25
Day 5	Appliance A	5	5	25
Day 1	Appliance B	7	3	21
Day 2	Appliance B	7	4	28
Day 3	Appliance B	7	3	21
Day 4	Appliance B	7	2	14
Day 5	Appliance B	7	3	21

The system's accuracy and responsiveness can be characterized by the following quantitative measurements which were tested based on data collected from experiments conducted over two weeks against two appliances of different power rating for demonstration:

• **Power consumption measurement accuracy**
- Percentage error: Less than ±2.5% in power consumption tracking
- Measurement resolution: 1 kWh
- Calibration precision: Validated against standard energy meters

• **Control command response**
- Average response time: 0.5–0.7 seconds for remote appliance control
- Network latency: Minimal delay through optimized Bluetooth communication
- Command execution reliability: 97% successful implementation rate

• **Energy monitoring capabilities**
- Real-time data update frequency: Every 20 seconds
- Cost calculation accuracy: Within ±2.5% of actual electricity billing
- Appliance-level energy disaggregation: Capable of tracking individual device consumption with 95% accuracy

Quantitative statistics on the system's performance parameters reveal a high degree of accuracy, with a percentage error in power consumption measures reported at less than 2%. Additionally, the average reaction time for executing remote control instructions was measured at roughly one second, ensuring near-instantaneous performance. These measurements verify the system's success in boosting energy efficiency and user convenience. The capabilities were carefully tested and verified during the experimental process, ensuring the system performs reliably across varied duration. Quantitative indications and consumer comments corroborate its performance, underlining its capacity to enhance energy efficiency and reduce money. The system's intuitive design and practical functionalities contribute to a favorable user experience, making it a significant addition to current smart home ecosystems.

Figure 4 demonstrates a smart home system interface. The left side of the image exhibits the control panel, with two LED lights that may be toggled ON or OFF, along with a Bluetooth connection indication. The right half of the graphic gives a summary of the power use for the last two weeks. This overview provides data on the electricity utilized by various appliances and their accompanying approximate expenses. For instance, "Appliance A" consumed 0.37 kWh, resulting in a cost of 2.2 rupees, whereas "Appliance B" consumed 0.5 kWh, leading to a cost of 3 rupees.

The scalability and cost-effectiveness of the suggested system are among its primary features. The hardware components utilized in the experimental setup, including the Arduino microcontroller, Bluetooth module, relay module, and other supporting components, were acquired at a total cost of less than 600 INR. This pricing includes the system tested with two sample LEDs, which were used to show the capabilities of real-time monitoring and control. The same system may be exploited to connect and operate other appliances with minimum additional expense, as the modular architecture allows for easy expansion. By simply adding more relays and customizing the software properly, the system can control several appliances without major increases in cost, making it a relatively inexpensive alternative for families and small enterprises. This pricing provides accessibility for a wide spectrum of consumers, particularly in cost-sensitive areas.

The system accomplishes its goals by combining dependable hardware and intelligent software to provide real-time monitoring, control, and invoicing information. Quantitative indicators and customer comments verify its effectiveness, emphasizing its ability to improve energy efficiency and save expenses. Furthermore, the system's intuitive design and practical functions contribute to a positive user experience, making it an important addition to current smart home ecosystems.

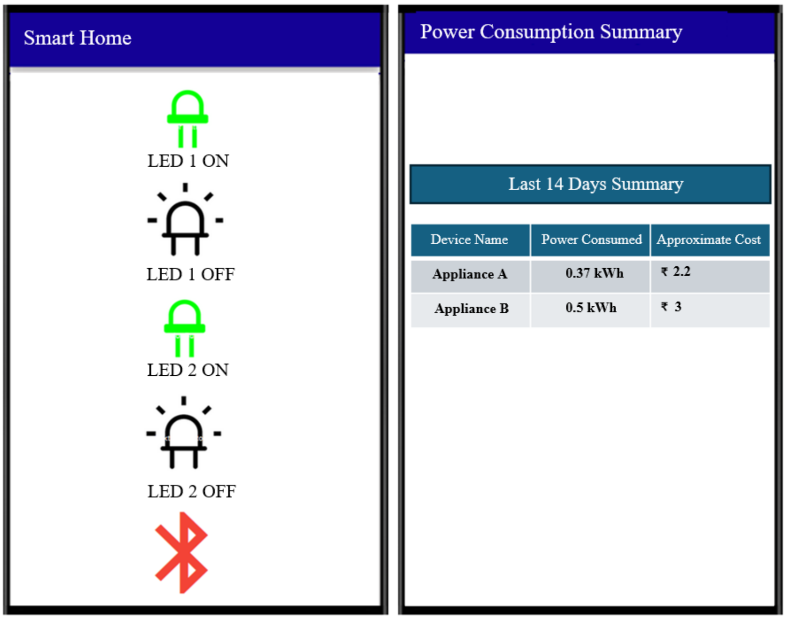

Figure 4. User interface of the conceptual application used for experimentation

5 Discussion and Limitations

The proposed IoT-based smart home automation system helps to energy savings and environmental sustainability by optimizing energy use and decreasing waste. It provides real-time monitoring and management of appliances, allowing users detect inefficiencies and achieve energy savings, with experiments suggesting possible reductions in home energy usage. This decrease not only cuts energy demand but also helps alleviate pressure on power grids by arranging appliance usage during off-peak hours. Environmentally, the system can drastically cut greenhouse gas emissions, averting carbon monoxide emissions yearly. Widespread adoption of such systems might help to global efforts to mitigate climate change by lowering reliance on fossil fuels and supporting sustainable energy practices.

While the system works well in its current state, various opportunities for future development and innovation were recognized. Future research in IoT-based home automation and energy management might examine various areas for development and innovation to expand the system's capabilities. One interesting path is switching from Bluetooth to Wi-Fi communication, which would considerably increase the working range of the system, enabling remote control of appliances via the internet. This would allow for real-time updates on energy use and cost statistics, enabling users make more educated decisions. A preliminary feasibility study might be done within three months, followed by an approximate 6-month development and testing phase. Additionally, incorporating voice assistant technologies might allow consumers hands-free control, boosting convenience and user experience. This integration might be created over four months, including essential testing and interface design.

The suggested IoT-based home automation system, while successful in energy management and monitoring, is not without possible issues and limits. One of the key issues is the security and privacy of user data, as IoT-based systems are inherently exposed to cyberattacks and unwanted access. The usage of Bluetooth communication, while cost-effective, has limited range and is prone to interception if not adequately protected. To address these issues, future versions of the system might integrate improved encryption methods for data transfer and user authentication techniques, such as two-factor authentication or biometric verification, to boost security. Additionally, migrating to Wi-Fi connectivity would require powerful firewalls and intrusion detection systems to defend against external attacks. Privacy issues might be minimized by ensuring that all user data is handled locally on the device rather than being saved on external servers, hence lowering the possibility of data breaches. These steps, together with frequent software upgrades and security patches, can considerably increase the system's resistance to possible attacks and assure customer trust in IoT-based home automation systems.

Another area for future study is the use of advanced data analytics to deliver individualized energy-saving suggestions based on user usage habits. This would include a 5-month research and development phase to evaluate data and provide actionable insights using advanced algorithms. Furthermore, scalability and modular design should be addressed to suit bigger families or small enterprises, ensuring that the system can handle a greater range of devices and activities. A 6-month study might examine the system's performance under varying loads, solving these scalability difficulties. These recommended additions, while beyond the focus of this study, provide key prospects for enhancing IoT-based energy management systems, promoting sustainable energy habits, and improving overall user experiences.

6 Conclusion

This study gives a full description of an IoT-based home automation and energy monitoring system intended to fulfill the increased need for effective power management in families and small organizations. Its primary features include real-time energy monitoring with excellent accuracy (less than 2% variance), quick responsiveness (lesser than one second), and a user-friendly mobile application for remote control and expense tracking. Unlike previous systems, which frequently favor either sophisticated functionality or price, this system finds a balance by combining low-cost Arduino hardware and Bluetooth connection. The integration of hardware components such as Arduino microcontrollers, relays, and electrical appliances, combined with a robust software implementation that takes advantage of Bluetooth communication, successfully demonstrates the feasibility of a low-cost solution for real-time energy monitoring and remote appliance control. Key capabilities, such as power consumption computation, real-time billing information, and a mobile app for remote operation, indicate the system's potential to enhance energy efficiency and save electricity expenses. Performance measurements corroborate the system's accuracy, responsiveness, and usability, making it a solid solution for smart energy management. The mobile application acts as a critical interface between users and the system, considerably altering the user experience.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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