Development and evaluation of a smart home energy management system using internet of things and real-time monitoring

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ABSTRACT

This project presents the design and implementation of a smart home energy management system using internet of things (IoT) technology to optimize household energy consumption. The system integrates various sensors, including passive infrared (PIR), light dependent resistor (LDR), and DHT11, to collect real-time environmental data, which is processed by a NodeMCU microcontroller. The microcontroller controls home appliances using relays, while the Blynk mobile app and Streamlit web platform provide users with remote monitoring and control capabilities. Despite successfully optimizing energy usage, the system faces limitations such as high sensor sensitivity and potential hazards during high-load power demonstrations. To address these issues, future work proposes integrating additional sensors for improved accuracy and incorporating renewable energy sources for increased sustainability. This project aims to enhance energy efficiency, provide users with greater control over their energy consumption, and contribute to smart home automation by utilizing real-time data, IoT integration, and user-friendly interfaces.

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1. INTRODUCTION

Electricity has become a necessity for survival in the modern world, with our growing dependency making it crucial to use energy resources effectively. One effective method to achieve efficient energy use is through optimizing the consumption of energy resources in homes, which can be accomplished in an eco-friendly manner by implementing an energy management system, such as a smart home [1]. Smart home technology allows for more efficient resource use while reducing waste, benefiting both the environment and homeowners' finances [2], [3]. This project proposes a smart home energy management system, which aims to reduce electricity bills and overall expenses by automatically detecting excessive power consumption from faulty appliances and taking preventive measures through automated controllers. However, there are challenges in implementing such an energy management system effectively. One major challenge is the reluctance of homeowners to adopt energy-efficient technologies due to concerns about initial costs and a lack of awareness regarding the long-term benefits [4], [5]. Another challenge is the issue of standby power consumption, where household appliances continue to draw electricity even when turned off, leading to higher utility bills [6], [7]. Addressing these challenges requires user-friendly smart home technologies, like those applied in this project, which can detect unnecessary energy usage and automatically cut off power to appliances not in use. This project presents a practical solution for reducing energy consumption, improving efficiency, and making energy management more accessible to homeowners.

2. LITERATURE REVIEW

The concept of a smart home revolves around interconnected devices that utilize artificial intelligence to optimize energy use and enhance user control. User control is a fundamental aspect in achieving the integration of diverse smart home functionalities, as it allows users to manage energy consumption effectively and tailor their home environment to specific needs [8], [9]. However, while smart homes have been successful in improving energy efficiency and providing enhanced security, a gap exists in focusing specifically on energy management systems like the home energy management system (HEMS) [10], [11]. Systems like HEMS are designed to balance energy demands by collecting data from various household devices, analyzing consumption patterns, and optimizing the power flow to reduce wastage [12]. Although smart homes integrate various technologies to automate tasks, the emphasis on security features often overshadows energy optimization. Optimization of energy, beyond simply enhancing efficiency, requires advanced predictive models that can learn and adapt to household consumption behaviors, integrating renewable energy sources and energy storage units where possible [13]. Addressing this gap by prioritizing energy management over security would provide homeowners with better cost savings and contribute more significantly to sustainability [10]. Sustainability in smart homes can also be supported by machine learning algorithms that predict energy usage trends, enabling smarter load management and fostering a balance between energy demand and available supply [14], [15]. The internet of things (IoT) is integral to smart home technology, enabling devices to connect and exchange data effectively [16]. Effectively utilizing IoT technologies involves leveraging various communication protocols to ensure seamless connectivity between all components within the home ecosystem, thereby facilitating real-time monitoring and control [17]. Despite the availability of advanced communication technologies like Wi-Fi, ZigBee, and Bluetooth, there is still a gap in choosing the most suitable technology for specific smart home applications [18], [19]. Applications for energy management need technologies that not only guarantee connectivity but also prioritize minimal energy consumption to maximize efficiency, especially during peak operation periods [20]. Wi-Fi, for example, offers high-speed data transfer but may consume more power compared to other technologies, while ZigBee and Bluetooth provide energy-efficient alternatives with certain limitations in data rate and range [21].

Range considerations, alongside the need for reliability in data communication, suggest a hybrid communication approach, potentially combining different technologies to mitigate the disadvantages of individual protocols and thereby enhance the efficiency of smart home systems. This inconsistency creates a challenge in optimizing energy, especially when attempting to reduce power consumption comprehensively in a smart home environment. To address the gaps highlighted, this project proposes an IoT-based smart home energy management system focusing on power consumption reduction rather than security features. Features of such a system should include intelligent scheduling and load prioritization to adjust consumption patterns in real-time, thereby minimizing peak loads and preventing energy overuse [22]. The system will leverage communication technologies, with Wi-Fi being chosen for its fast data transfer capabilities, despite the potential trade-offs in power consumption. Consumption monitoring will be complemented by intelligent energy analytics, providing homeowners with insights into usage behaviors, thereby encouraging more responsible energy use [23]. Prioritizing energy management through real-time monitoring and control will help achieve substantial energy savings for homeowners. Thus, developing an efficient communication system tailored for energy management will ensure effective control and reduced utility bills, addressing the gaps in existing smart home systems.

3. METHOD

The project followed an iterative IoT methodology inspired by design thinking [24], [25]. The process involved six phases: cocreate, ideate, question and answer, IoT OSI, prototype, and deploy. The development of the smart home energy management system involved creating software for IoT-enabled components and integrating sensors such as passive infrared (PIR), light dependent resistor (LDR), and temperature sensors for effective monitoring and control of energy consumption. The Blynk platform was used to develop a mobile application that allows remote control and monitoring of connected appliances.

3.1. System architecture

The system architecture of the smart home energy management system, as illustrated in Figure 1 (see below), was used in this project to enable efficient communication between various components, allowing homeowners to effectively manage energy consumption. Energy consumption was monitored through sensors, which collected data and sent it to the NodeMCU microcontroller for processing. The NodeMCU microcontroller was connected to the Blynk cloud service via the ESP8266 Wi-Fi module, providing remote access capabilities. Remote access through the Blynk platform allowed users to interact with the system through their mobile devices, giving them flexibility in monitoring and controlling appliances. Appliances such as fans, lamps, and irons were controlled using relay modules, which received signals based on the processed sensor data. The sensor data was used to make real-time decisions regarding energy consumption, enhancing the system's overall efficiency and user convenience.

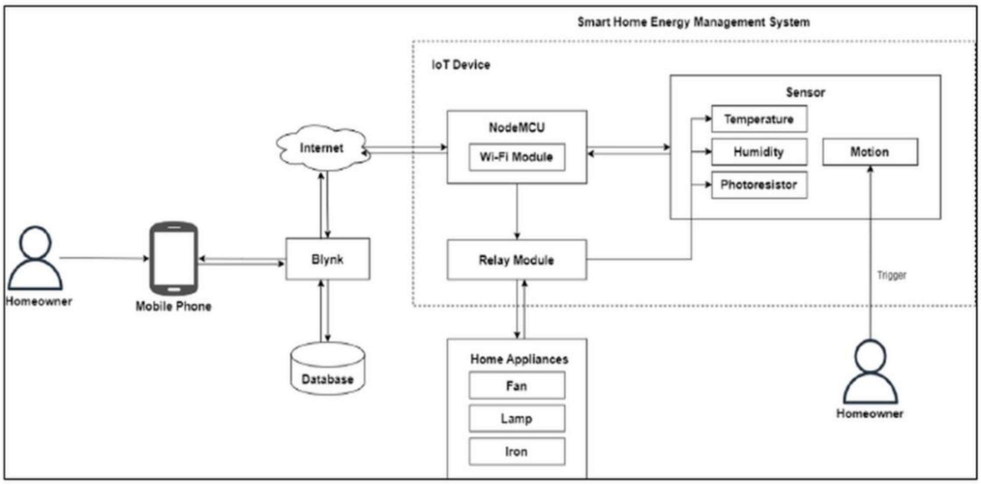

Figure 1. System architecture

3.2. Sensor integration

The system employs multiple sensors to enhance automation and optimize energy consumption within the smart home environment. The passive infrared (PIR) sensor detects motion, enabling the system to turn lights and appliances on or off based on occupancy, thereby minimizing unnecessary energy usage. The LDR sensor measures ambient light intensity, allowing automated lighting control to ensure that artificial lights are only activated when natural light is insufficient. Additionally, temperature and humidity sensors, such as the DHT11, monitor environmental conditions and help regulate appliances like fans and air conditioners for efficient climate control. The integration of these sensors ensures real-time data collection, which is processed by the NodeMCU microcontroller to make intelligent energy-saving decisions.

3.3. Mobile application development

The mobile application, developed using the Blynk platform, serves as the primary interface for users to interact with the smart home energy management system. Through the application, homeowners can remotely monitor real-time energy consumption and control various household appliances via a user-friendly dashboard. The app supports automation features that allow users to set predefined rules based on sensor inputs, such as scheduling appliances to turn off during low occupancy periods or adjusting lighting based on ambient conditions. Additionally, the application provides historical energy usage data, helping users analyze their consumption patterns and make informed decisions to improve efficiency. By leveraging IoT connectivity, the mobile application enhances accessibility, allowing users to manage their home energy systems from anywhere, promoting convenience and sustainability

4. RESULTS AND DISCUSSION

The development of the smart home energy management system began with designing the schematic circuit diagram, which served as the foundation for integrating various components into a cohesive unit. The circuit diagram in Figure 2 illustrated the connections between key components, including the NodeMCU microcontroller, relay modules, sensors, and the basic home appliances. This design ensured that each component played a specific role in optimizing energy use in the smart home energy management system. To control and monitor the system, platforms like Blynk and Streamlit were utilized to provide a seamless user experience. Blynk, as represented in Figure 3, offered an interactive mobile interface that allowed users to remotely control home appliances, enabling convenient energy management from anywhere. In addition, Streamlit served as a web-based tool in Figure 4 for visualizing data, giving users deeper insights into their energy usage patterns and allowing them to make informed decisions about optimizing consumption. The Arduino IDE played a critical role in configuring the NodeMCU and integrating it with both Blynk and Streamlit. This combination of hardware and software platforms enabled smooth interactions between components, allowing users to gain full control over their energy consumption in a user-friendly manner.

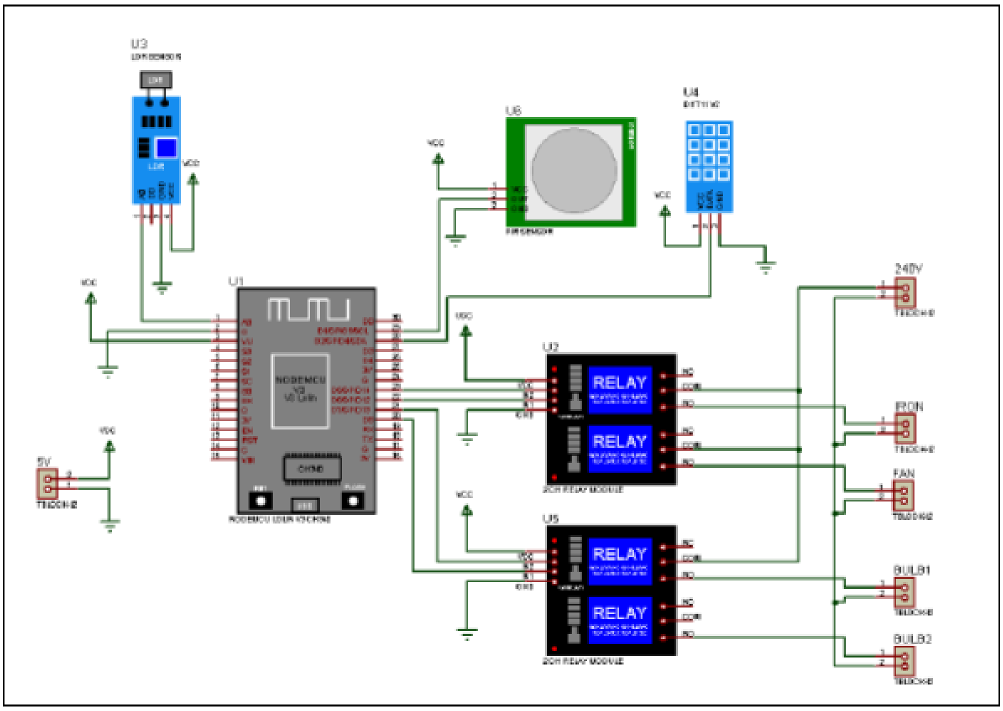

Figure 2. Smart home energy management system

Figure 3. Interface of Blynk mobile application

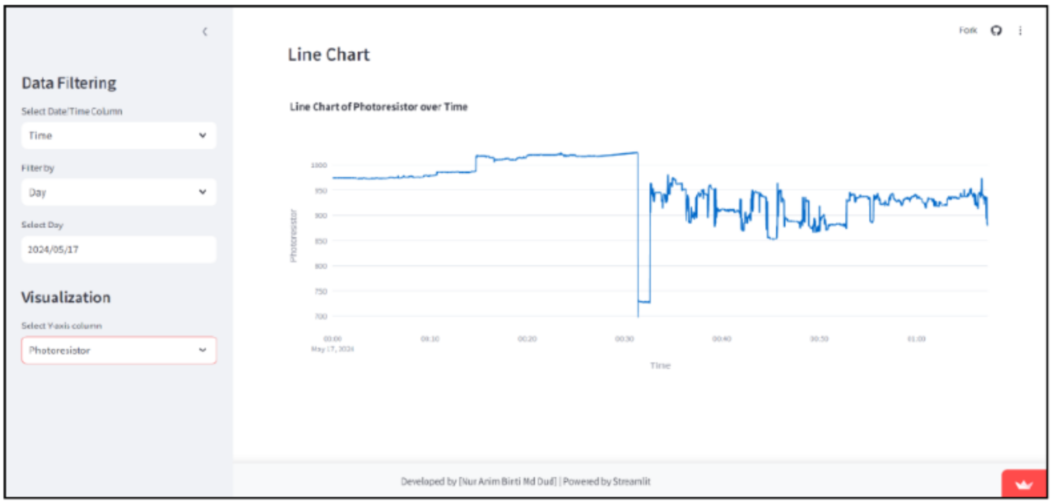

Figure 4. Interface of streamlit

The primary functions of smart home energy management system were implemented through Arduino IDE programming, using sensor data to make decisions regarding appliance control. The PIR (motion sensor), LDR (light intensity sensor), and DHT11 (temperature and humidity sensors), provided essential information about environmental conditions, which was used by the system to automate control actions. The relay modules responded to these sensor inputs, enabling actions like switching off lights when no motion was detected, thus reducing unnecessary power consumption. The overall functionality was demonstrated through a project prototype in Figure 5, which integrated all components into a fully working system. The prototype was rigorously tested to ensure its efficiency and reliability, showing that smart home energy management system could effectively manage household energy consumption while interacting seamlessly with Blynk and Streamlit interfaces. The successful implementation of smart home energy management system highlighted its ability to enhance energy efficiency while providing users with an accessible and intuitive way to control their home environment.

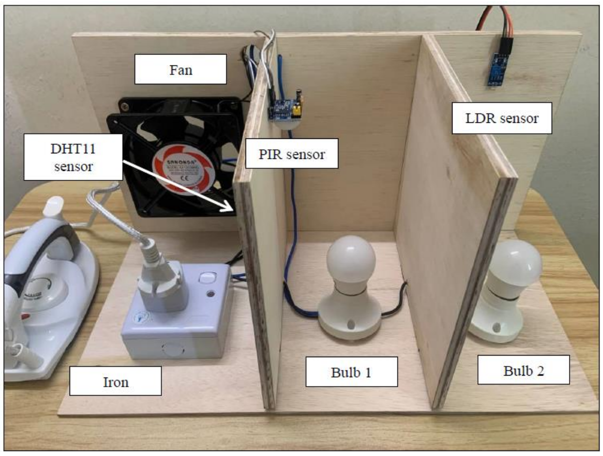

Figure 5. Project prototype

Table 1 presents the funtionality test perform in this project, which focuses on analyzing the performance of the smart home energy management system components. The results demonstrated that the implemented system components, including the DHT11, LDR, and PIR sensors, met the expected requirements under various environmental conditions. Table 1 also indicated the accuracy and reliability of the DHT11 sensor in measuring temperature and humidity through repeated testing, illustrating the sensor's suitability for smart home applications.

Table 1. Summary of functionality testing

No.	Components, sensors, & system	Scenario	Expected result	Status
1	DHT11 sensor	Put under low temperature surrounding	Reading of temperature will be low, less than 32	👍
		Put under high temperature surrounding	Reading of temperature will be high, more than 32	👍
		Put under low humidity surrounding	Reading of humidity will be low, less than 80	👍
		Put under high humidity surrounding	Reading of temperature will be high, more than 80	👍
2	LDR sensor	Put under low light intensity surrounding to indicate it is dark	Reading of light intensity will be high, more than 1000	👍
		Put under high light intensity surrounding to indicate it is bright	Reading of light intensity will be low, less than 1000	👍
3	PIR sensor	Movement is made in front of the sensor to demonstrate motion	Reading of the sensor will be recorded as an event in Blynk	👍
4	Clothes iron	Automatically turn off when the temperature is higher than 32	Clothes iron will turn off	👍
5	Fan	Automatically turn on when the temperature is higher than 32	Fan will turn on	👍
		Automatically turn off when the temperature is lower than 32	Fan will turn off	👍
6	Bulb 1	Automatically light up for 10 seconds when movement is detected	Bulb 1 will light up for 10 seconds	👍
7	Bulb 2	Automatically light up when the light intensity is more than 1000	Bulb 2 will light up when the light intensity is more than 1000	👍
		Automatically turn off when the light intensity is lower than 1000	Bulb 2 will turn off when the light intensity is lower than 1000	👍
8	Control and monitor using Blynk mobile application	Used to control the home appliances, display input from the sensors	Blynk mobile application is used to turn on and off all the appliances	👍
9	Control and monitor using Blynk web application	Used to control the home appliances and display input from the sensors	Blynk web application is to turn on and off all the appliances and display input from the sensors	👍
10	Monitor history sensor data using Streamlit	Display historical sensor data	Historical sensor data will be displayed	👍
11	Calculate the energy consumption of home appliances	Calculate the energy consumption of each appliance in watt-hours (Wh) by multiplying the power rating by the operation time	The amount of energy used by each appliance is calculated and displayed in watt-hours (Wh)	👍

Similarly, the LDR sensor effectively responded to changes in light intensity, as confirmed by the performance metrics in Table 1, contributing to the overall automation of home appliances. The PIR sensor also proved to be consistent in detecting motion, which was instrumental in enhancing the system's automation and security features. Table 1 also highlights the successful integration of these sensors with the control mechanisms of household appliances. Further, system components such as the iron, fan, and bulbs responded accurately to sensor inputs, demonstrating effective interaction between the hardware and software components. This seamless integration facilitated the precise control of appliances based on real-time sensor data, thereby improving energy efficiency and automating daily household tasks. Additionally, Table 1 also highlights the reliability of the Blynk mobile and web applications in providing an efficient interface for system monitoring and control, allowing users to access system functions remotely. This user-centric approach, which enabled convenient and effective interaction with the system, further enhanced the practicality of the proposed solution for energy management in real-life scenarios.

5. CONCLUSION

The smart home energy management system developed in this project successfully addressed the need for efficient energy management within homes by integrating IoT technologies for enhanced monitoring and control. The project utilized sensors, relays, and mobile applications to optimize energy usage, ultimately contributing to the reduction of utility costs. However, several limitations were identified, such as the high sensitivity of the PIR sensor and the hazards associated with demonstrating high-load power sources. These limitations highlighted the need for improving component reliability and safety to ensure the robustness of the system in real-world applications.

To overcome these limitations, future work should focus on incorporating additional sensors for enhanced data accuracy and integrating renewable energy sources like solar panels to reduce dependency on high-load power sources. By improving system accuracy and adopting sustainable energy solutions, the project aims to increase its overall efficiency and safety. These proposed future developments will not only enhance the system's effectiveness but also ensure a more environmentally friendly approach, providing a comprehensive solution for modern energy management needs in smart homes..

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C : **C**onceptualization
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P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

No conflict of interest.

DATA AVAILABILITY

The data that supports the findings of this study are available from the corresponding author [Mohamed Imran Mohamed Ariff], upon reasonable request.

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