

An IoT-Enabled Smart Energy Management System to Improve Energy Efficiency in University Laboratory

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Abstract: Efficient energy management remains a challenge in university laboratories. The aim of this study is to develop and deploy an Internet of Things (IoT) system that can automatically adjust electronic devices to improve the efficiency of power consumption in the university laboratory. An advanced system is urgently needed to support sustainable and effective energy management. A smart IoT-based energy management system can improve energy efficiency, reduce operating costs, and reduce negative environmental impacts. The system enables both human and automated control of lighting and air conditioning using scheduling and occupancy detection. This development-based research uses a product design methodology that includes both software and hardware. The software product in this research is an IoT platform website for managing IoT devices. The essential processes include defining project goals and requirements, designing a system architecture, creating a user experience design, developing and integrating components, and conducting tests. The system is successful in automatically monitoring and controlling electronic devices based on certain parameters such as scheduling and presence detection. The system meets most of the specified functional and non-functional requirements as demonstrated in experiments, although it is somewhat limited by hardware limitations. Ultimately, the system increases the energy efficiency of the laboratory and thus successfully fulfills the research goal. This innovative project could be a blueprint for other smart energy control efforts.

Keywords: Automated control; Efficient energy management; Energy management system; Internet of Things; Presence detection

INTRODUCTION

The need to address the world's energy problem and environmental degradation is now more urgent than ever. As stated by (Zulaykha Khurshid Dijoo & Rizwana Khurshid, 2022), environmental degradation is caused by human activities such as industrialization and urbanization, therefore research and implementation of green technologies can help mitigate environmental degradation. In science, the duty to be a role model in sustainable practices is crucial because education and innovation intersect (Laura Dryjanska et al., 2022). Recognizing its duty, the Informatics Engineering Laboratory at Pontianak State Polytechnic (POLNEP) is working to integrate the latest technological breakthroughs into its energy management systems. The implementation of the Internet of Things (IoT) is leading the way in revolutionizing resource management in the education sector and promoting intelligence and environmental friendliness (S. T. Siddiqui et al., 2023).

This project aims to reduce energy consumption and promote an environmentally conscious culture in educational institutions. The Informatics Engineering Laboratory is the central hub for this unique project, demonstrating the practical and meaningful application of IoT-based systems. The implementation of this system is intended to serve as an outstanding example of the practical benefits of intelligent technology in real-world scenarios. This study focuses on the creation and commissioning of an IoT-controlled energy management system tailored to the specific needs of POLNEP's Informatics Engineering Laboratory. The system's architecture is designed to incorporate multiple sensors over a network to automate the control and optimization of energy consumption. The technology controls energy consumption based on room occupancy and environmental parameters to save waste.

The current procedures at the Informatics Engineering Laboratory, which require manual intervention to regulate temperature and lighting, represent a notable opportunity for improvement. Previous studies has already been carried out in the same place, but are still limited to the monitoring electrical energy consumption (Wibowo et al.,

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2023). Similar work was also carried out by (Wen-Jye Shyr et al., 2018) using a WebAccess. The study proposes the use of IoT technology, specifically the WebAccess system, for energy management, highlighting the potential of IoT in optimizing energy consumption and control. Some similarity can also be found with this work and the work of (J. Yasuoka et al., 2022). The project focuses on the energy consumption of the air-conditioning system and enables energy efficiency actions through the use of monitored data, user behaviors, and feedback. It emphasizes the importance of user engagement, awareness, and investment in energy efficiency to achieve efficient use of resources. Conceptually similar work has also been carried out by (Georgios Mylonas et al., 2019), using maker community tools and IoT technologies in European schools to promote behavioral change for sustainability and energy awareness. It reports on the implementation of a large-scale IoT deployment in educational buildings, along with a "Maker" lab kit activity and a serious game. Integration of these activities into the curriculum will also be discussed, along with feedback from workshop activities in several schools. The first results show strong acceptance in the school community.

Creating an intelligent system that automates procedures and adapts to usage patterns could transform the way energy is managed in laboratory environments. The proposed system provides real-time monitoring and control to reduce risks from voltage fluctuations and other electrical anomalies that could impact laboratory operations. It is very important to keep the voltage stable in a laboratory to avoid light flickering or malfunction of connected devices (Perera & Elphick, 2023). The purpose of the study is to gain important insights into the behavioral changes that IoT technology can induce in laboratory users. The technology could act as a catalyst for a broader cultural shift towards sustainability and environmental protection among the university population by encouraging a more mindful and data-driven approach to energy consumption. The study in POLNEP's Informatics Engineering Laboratory aims to improve technology and promote sustainable and conscientious energy management in educational institutions. The expected results of this research include a significant reduction in energy costs towards a more sustainable future and an improvement in operational effectiveness.

LITERATURE REVIEW

There are several studies that are referenced in this study. In the face of the urgent need for sustainable energy practices, the integration of IoT-based smart energy management systems in university laboratories has emerged as a crucial solution. According to (Pedro Moura et al., 2021), university buildings can achieve energy sustainability through the use of IoT platforms. In particular, the focus of the research is the Faculty of Telecommunications Engineering at the Universidad Politecnica de Madrid, which offers an Internet of Things platform to achieve energy sustainability in academic buildings. This involves integrating renewable energy sources and tracking and controlling electricity consumption in order to make existing buildings almost completely energy-free. However, it is not specifically about intelligent energy management strategies for educational institutions.

The implementation and deployment of an IoT-based Smart Energy Management System (SEMS) for efficient energy management at the consumer side, as carried out by (M. Usman Saleem et al., 2021), highlights the far-reaching demand response and monitoring system for electrical and aggregated Devices and hardware capable of monitoring and evaluating network efficiency parameters in real time. It is stated that the data provided by the SMs will be used by power utilities to revolutionize power distribution and consumption through techniques such as non-intrusive load monitoring and demand-side management (DSM).

Building on this foundation, the incorporation of artificial intelligence (AI) into energy management systems, as advocated by (AI) in energy management systems, as advocated by (Mahmoud Elsisy et al., 2021; Mohamed El-Sayed M. Essa et al., 2023), illustrates a paradigm shift in energy optimization strategies for university laboratories. By using IoT-based approaches to identify energy saving opportunities and leveraging data-driven insights, universities can improve their energy management practices to promote sustainability and resource conservation. This research confirms that integrating IoT and AI can effectively address energy consumption issues in building management systems (BMS) by enabling intelligent systems and making data-driven decisions. However, the evaluation of the proposed BMS-based IoT approach is limited to experimental results and there is no mention of real-world implementation or scalability. Further validation in larger buildings and real-world scenarios is required.

In addition, the implementation of smart light control systems in university classrooms using IoT technology, as explored by (Francis Jesmar P. Montalbo & Erwin Enriquez, 2020), reflects an advanced approach to energy efficiency. By dynamically adjusting lighting levels based on occupancy and environmental factors, these systems optimize energy consumption without compromising lighting quality. Such advancements highlight the role of IoT-enabled solutions in maximizing energy efficiency, reducing costs, and promoting green practices in educational settings. The convergence of IoT technologies with energy management systems marks a transformative era in sustainable energy practices in university classrooms. Although some progress has been made, further research is needed by integrating the smart lighting system with other IoT devices in the classroom for a more comprehensive and efficient control system.

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Similarly, the design and implementation of an IoT platform for remote monitoring and control of smart buildings in general, as studied by (Mohamed A. Ahmed et al., 2022), represents a concrete example of IoT-enabled energy management practices. The platform enables data collection for energy consumption, data storage and visualization using various sensor nodes and measuring devices. The solution was designed, implemented, and tested on a university campus, considering three scenarios: an office, a classroom, and a laboratory. The aim is to enable building automation, minimize electricity consumption costs and ensure comfort for the end user. By using IoT-enabled technology to monitor energy consumption and inform energy management activities, this study confirms the practical impact of IoT applications in improving energy efficiency in academic environments. Researching IoT technologies in the real context of university laboratories offers valuable insights for designing sustainable energy practices.

Finally, a review of the use of IoT-enabled technology for energy-efficient buildings and cities by (Karam M. Al-Obaidi et al., 2022) examines the potential of IoT-based solutions to promote sustainability in general buildings and cities. The study identifies the limitations and challenges that built environment professionals face when integrating IoT into buildings and cities, such as inadequate understanding of the technologies and limitations in implementation. By addressing these challenges and providing critical arguments, the paper provides insights and next steps for effectively leveraging IoT for energy efficiency. The results of the study can influence decision-making processes for professionals in the built environment and enable them to make informed decisions about IoT technologies and their application for energy saving.

METHOD

The methodology used in this research is a product development approach consisting of software and hardware in one project (Desai, 2015). Fig. 1 shows the phases of the methodology used. Compared to the software development methodology, this methodology has some additional steps, especially in the planning section. In general, the following steps were taken: (1) defining project objectives; (2) defining project requirements based on project objectives; (3) system architecture design; (4) defining user experience (UX) flows; (5) identification of parts/stages of development; (6) assembling the hardware and creating the program code for each part/step; (7) integration of each section/step; and (8) testing and troubleshooting. In addition to these phases, there are other iterative activities that connect Step 4 with Step 3 and Step 8 and Step 6.

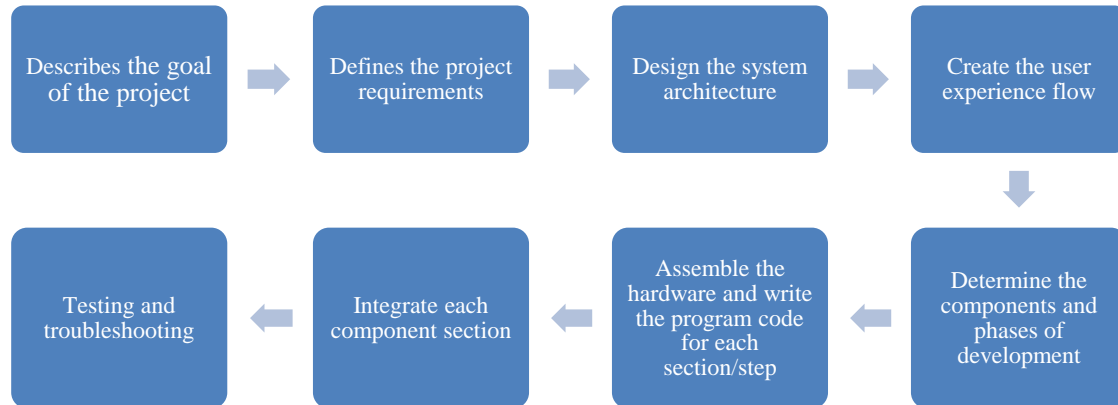


Fig. 1 Research Flow

In the first phase of the research methodology, the research objectives are determined, including the development of an IoT system for automatic control of devices in the POLNEP's Informatics Engineering Laboratory. The research focuses on the use of IoT for energy efficiency. After defining the purpose of the research, the next step is to determine the project needs on the research. In this second phase, hardware and software requirements are defined. Besides, the functional and non-functional requirements of the system are also determined. Table 1 shows software and hardware requirements, whereas Table 2 shows the functional and non-functional requirements of the systems to be built.

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Table 1. Hardware and software requirements

No	Type	Product name	Description
1	Hardware	Smart wall switch 3 gang	1 pcs
2	Hardware	Smart wall switch 2 gang	9 pcs
3	Hardware	Smart infra-red	8 pcs
4	Hardware	Zigbee humidity and temperature sensor	8 pcs
5	Hardware	Google nest mini 2nd gen	2 pcs
6	Hardware	Zigbee gateway	2 pcs
7	Hardware	Zigbee motion sensor	8 pcs
8	Software	Home Assistant	Version 2023.5.4
9	Software	ESPHome	Version 2.2.2
10	Software	Tasmota	Version 11.0.0

Table 2. Functional and non-functional requirements

No	Type	ID	Statement
1	Functional	FR1	The system can turn on the lights and air conditioner on certain days and hours.
2	Functional	FR2	The system can turn on the lights depending on the presence of people in the room.
3	Functional	FR3	The system can adjust the mode, fan speed, and temperature of the air conditioners via the dashboard.
4	Functional	FR4	The system can adjust the mode, fan speed and temperature of the air conditioners based on the environmental parameters in the room.
5	Functional	FR5	The system can send messages via Telegram when the status of lights and air conditioners changes.
6	Functional	FR6	The system can be controlled via voice commands from the Google Assistant.
7	Functional	FR7	The system can display reports about electricity consumption based on specific time intervals (per day, week, month and year).
8	Non-functional	NFR1	Realtime data is presented in the form of graphs/charts with a minimum time interval of 60 seconds
9	Non-functional	NFR2	Telegram notifications can be sent in less than 1 minute.
10	Non-functional	NFR3	Voice commands via Google Assistant can be executed by the system in less than 10 seconds.

The next step is to design the architecture of the system. As part of this research, several smart IoT devices will be installed in the laboratory, including: 1) motion sensors; 2) temperature and humidity sensor; 3) door sensors; 4) infrared controller; and 5) smart switches. The IoT devices are connected to the IoT platform via two methods: Zigbee and WiFi. The motion sensors, door sensors, temperature and humidity sensors connect to the IoT platform via Zigbee gateway, while the infrared controllers and smart wall switches connect via WiFi. The telemetry data from the IoT device is then sent to the MQTT broker running on the Mosquitto via the MQTT protocol. The IoT platform is designed to process data and present it in the form of dashboards so that users can access it via web browsers using the HTTP protocol from both mobile devices and computers. Fig. 2 shows the architectural design of the currently identified system.

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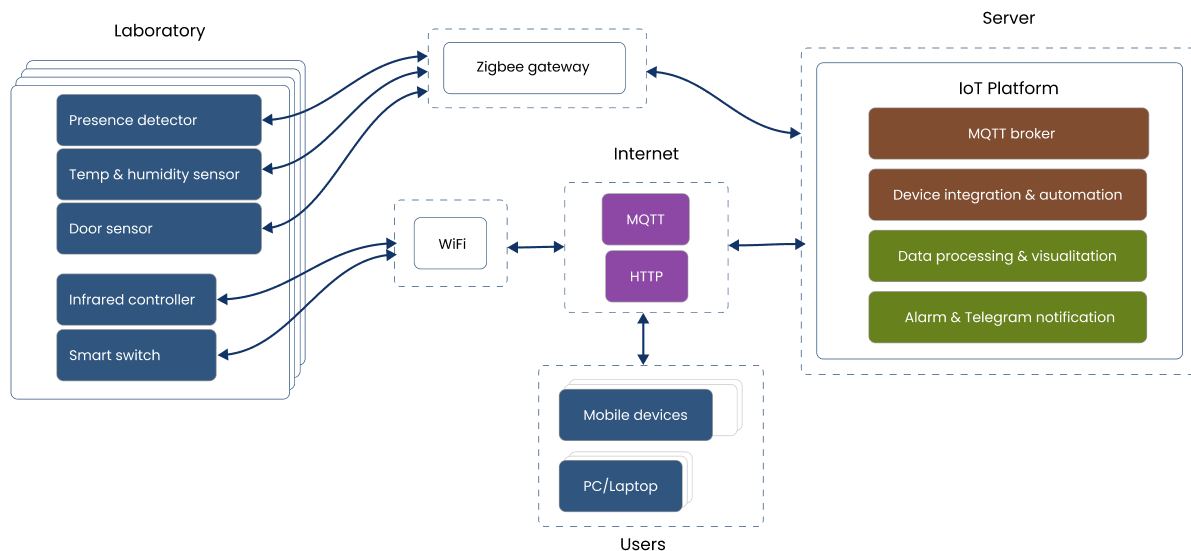


Fig. 2 System Architecture

The next step is defining the user experience flow. In this phase, the usage flow is carried out from the user side. The intended users of this system are initially laboratory managers and technicians. Users have access to the application dashboard, which can be accessed directly from the Home Assistant interface. After the user interface and user experience are defined, the development parts of the project are created. At this point, the project of this study is divided into several smaller parts. These parts are then completed individually and then integrated as a whole.

The subsequent action is the hardware installation and the creation of the program code. In this phase, the identified project parts are then put together and the program code is created. The program code is implemented using the YAML markup language and Visual Studio Code as an Integrated Development Environment (IDE). The development parts are then integrated. In this phase, every part of the development that has been compiled and converted into program code is integrated.

The final step is testing and troubleshooting. This step is taken to ensure that the integrated parts work well and that no problems arise. The testing method is carried out using the black box testing method. Testing is carried out based on functional and non-functional requirements that have been defined and then evaluated with the parameters of the assessment procedure, as well as the assessment criteria.

RESULT

This research provides two main results, namely software and hardware. The software product in this research is an IoT platform website used to manage IoT devices. Currently, various IoT devices have been successfully integrated and configured to monitor electrical energy and control electronic devices such as lights and air conditioners in each room of the laboratory. When implementing IoT-based intelligent energy management, several pieces of software were created. The following are parts of the development in implementing IoT-based intelligent energy management in this research.

The ESPHome firmware was used to monitor electrical energy consumption in the university's computer laboratory building. In the input area, current transformer (CT) sensors are used in combination with the ADS1115 ADC to convert analog signals from CT sensors into digital signals. There are 3 CT sensors, each used to measure the phase lines used in the laboratory. The input is used to obtain the amount of current in each phase line while the voltage value is taken from another IoT device in the form of a smart plug with energy monitoring function. The apparent power in the power grid is then calculated from the current and voltage results. The firmware has been successfully uploaded and integrated into the IoT platform website. Fig. 3 shows the ESPHome power monitor interface.

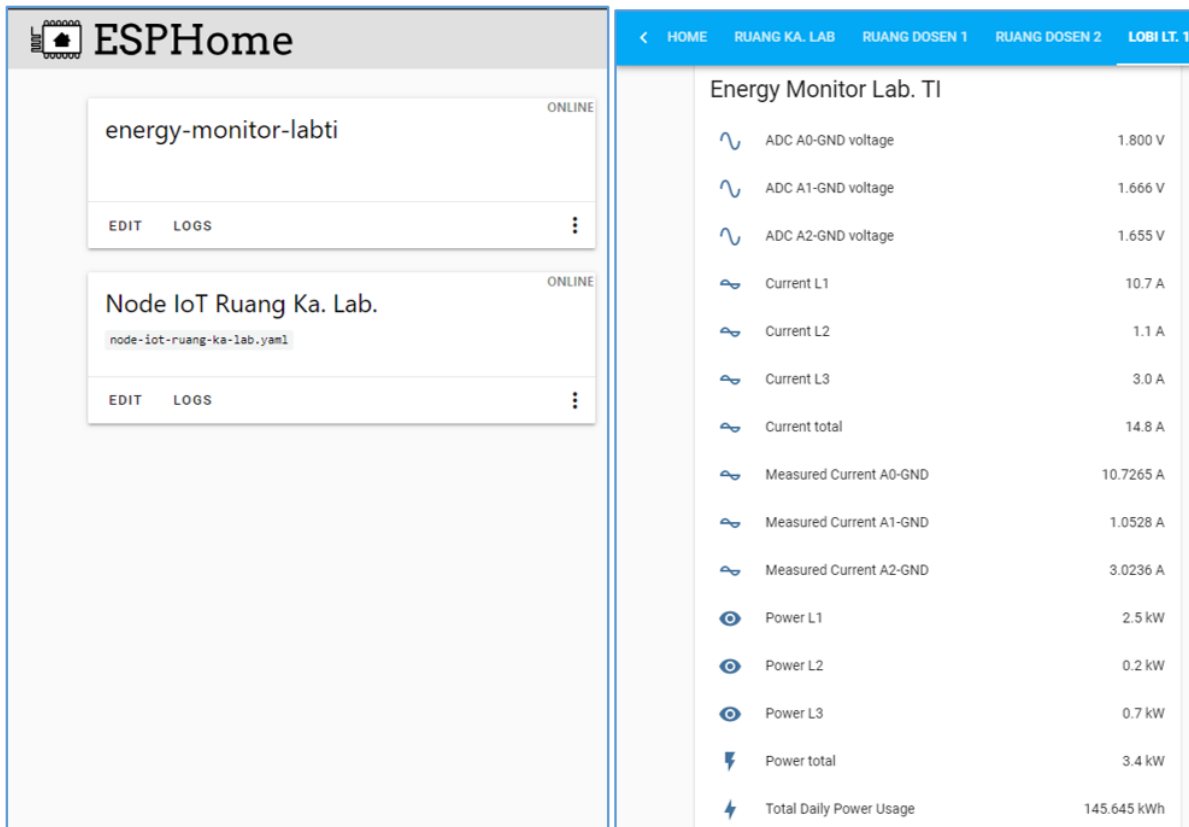


Fig. 3 Web Interface for Power Monitor

For Wi-Fi connected smart IoT devices, there are two integration methods for connecting to the IoT platform. The first way is to use a third-party provider, Tuya, and the second is to use Tasmota firmware. One of the challenges of using Tuya-based IoT devices is that users must rely on the cloud platform specifically provided by Tuya. In this research, Tuya-based devices are used in IoT devices to control lights (smart wall switches), while in universal smart infrared devices used to control air conditioners, Tasmota firmware is used, which can be controlled without depending on third-party clouds.

In addition to Tuya-based IoT devices that use WiFi technology, IoT devices that use Zigbee technology have also been successfully installed and configured. IoT devices that use Zigbee technology include door sensors, temperature and humidity sensors, occupancy detection sensors, and smart plugs. Apart from smart plugs, these IoT devices use energy sources that come from batteries. Therefore, Zigbee technology was chosen to maximize the use of batteries since the power consumption specifications in Zigbee-based devices are relatively small. On the other hand, the Zigbee based smart plug is used as a Zigbee network router, which is used to extend the range of the Zigbee network. In addition to routers, Zigbee networks also require a coordinator, a device that acts as the central manager and controller of the Zigbee network. In this study, a Zigbee coordinator with a Sonoff ZBDongle-E USB dongle connected to the Home Assistant as the IoT platform server via a USB Type-A interface was used. In Home Assistant, the Zigbee2MQTT add-on has been configured as software to manage Zigbee-based IoT devices. Fig. 4 shows the mesh network and the list of installed and configured Zigbee IoT devices.

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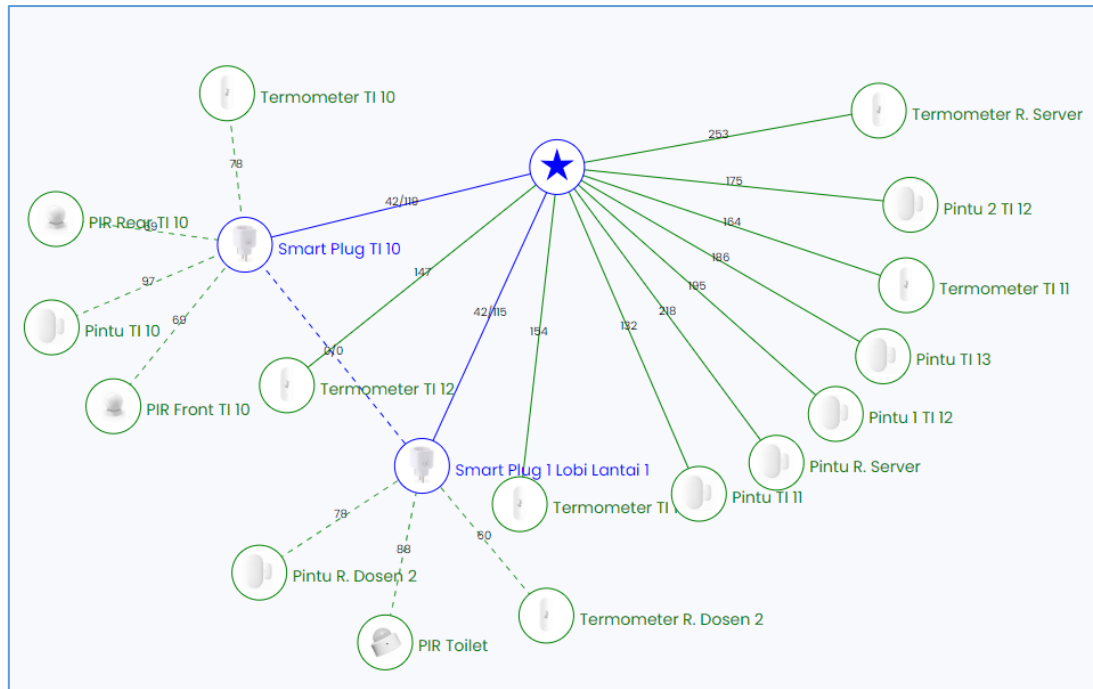


Fig. 4 Zigbee-based IoT Device Mesh Network

The device automation configuration was also successfully implemented. Automation is used to control the status of electronic devices such as lights and air conditioners and is categorized based on several parameters, namely time, the status of other devices (door sensors, occupancy detection sensors), or a combination of both. Currently, several automations have been successfully implemented, including setting the status of lights and air conditioning to ON on weekdays when the laboratory first opens. With this automation, technicians do not have to manually turn on the lights and air conditioning in each room in the morning hours when the lab is open. In addition to the time parameters, the automation also reads the status of the door so that the lighting and air conditioning remain in the OFF state when the door has not been opened. In addition, automation based on the status of IoT devices has also been applied to setting the status of lights in toilets using occupancy detection sensors with passive infrared (PIR) receivers. Fig. 5 shows the real-time dashboard of energy consumption on the Home Assistant IoT platform.

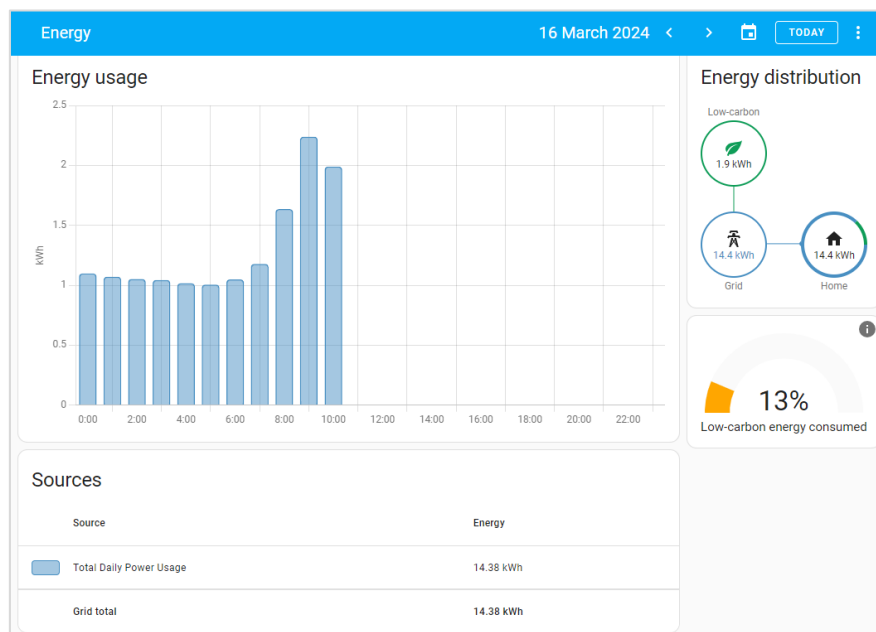


Fig. 5 Energy Dashboard on the IoT Platform

In the series of automation system tests for controlling lighting and air conditioning, the results show that the FR1 and FR2 requirements are perfectly implemented. FR1 testing shows the system can automatically manage

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lighting and room temperature settings based on a user-specified schedule. Turning lights and air conditioners on and off was tested twenty times through device testing using the automation feature in Home Assistant, and each test resulted in a device status change consistent with the settings. Meanwhile, FR2 has successfully demonstrated a responsive system that changes the status of lights based on presence sensors in the room, ensuring energy efficiency and user comfort.

Meanwhile, the FR5 and FR6 tests also delivered results that were in line with expectations. FR5 tests the system's ability to send notifications via Telegram whenever the status of lights and air conditioning changes. This testing is done through integration testing that results in consistent notification messages being sent very quickly after a status change. The FR6 test showed that the system can accurately respond to Google Assistant voice commands, indicating good integration between Home Assistant and the Smartlife app, as well as proper entity configuration within Google Assistant, allowing seamless control of IoT devices.

The FR3 and FR4 tests were also successfully passed thanks to the Tasmota firmware flashed into the IoT smart device with universal IR controller. On the other hand, the FR7 test successfully displayed accurate power consumption reports via the web application dashboard, providing daily, weekly, monthly, and annual energy consumption data. The NFR1 and NFR2 tests also showed impressive performance: NFR1 displayed real-time data in graph form with an update interval of every 60 seconds, and NFR2 was able to send Telegram notifications in less than a minute. NFR3 testing concluded the test with good performance, showing that the system was able to execute Google Assistant voice commands in less than 10 seconds, signaling high responsiveness and efficiency of the tested automation system.

DISCUSSIONS

The successful implementation of the functional requirements FR1, FR2, FR3, FR4, FR5, FR6 and the non-functional requirements NFR1, NFR2 and NFR3 demonstrates the robustness of the system in automating and integrating smart devices into the IoT platform. In particular, FR1 and FR2 demonstrate that the system is capable of performing scheduled and presence-based operations to control lighting and air conditioning (AC), which are core functions of a smart energy management system. The integration with Telegram for notifications (FR5) and the system's responsiveness to Google Assistant voice commands (FR6 and NFR3) within acceptable time frames demonstrate that the system can provide user-friendly interfaces and real-time interaction, essential to improving user experience.

The implementation of an IoT-based smart energy management system in POLNEP's Informatics Engineering laboratory has shown promising results. The system is successful in automatically monitoring and controlling electronic devices based on certain parameters such as scheduling and presence detection. The integration of various IoT devices, including energy monitors, motion sensors, temperature and humidity sensors, and smart switches, has enabled efficient energy use in the laboratory.

A comparison between the measured data from the energy monitors and the modelled data shows a significant improvement in energy efficiency. By automating the control of lighting and air conditioning based on occupancy and environmental conditions, the system effectively reduces energy wastage and optimizes energy consumption. Real-time data visualization through the Home Assistant dashboard provides users with valuable insights to track energy usage patterns and make informed decisions. Additionally, the integration of Tuya and Zigbee devices with Home Assistant shows that it is possible to manage various IoT devices on a single platform. Local control of Tuya devices and mesh networking capabilities of Zigbee devices increase system reliability and scalability.

Overall, the implementation of an IoT-based smart energy management system has shown great potential in improving energy efficiency, reducing operational costs, and minimizing environmental impact in a laboratory setting. These results highlight the importance of utilizing advanced technologies such as IoT to create smart and sustainable energy solutions for improved operational management and environmental conservation.

CONCLUSION

This research shows that using IoT to manage electrical energy in the university laboratory can increase the efficiency of energy use, reduce operational costs, and reduce negative impacts on the environment. It was found that the integration of Tuya and Zigbee-based IoT devices with Home Assistant enables effective control of electronic devices such as lights and air conditioners. In addition, the implementation of ESPHome firmware to monitor electrical energy usage has provided accurate and real-time information about energy consumption in the laboratory.

For future research, it is necessary to note several things that need to be improved. Firstly, further development needs to be done in terms of IoT device integration to cover more types of devices and sensors. In addition, it is also necessary to expand the scope of the Zigbee network to improve the efficiency of communication between devices. Although this research successfully achieved its goals, there are still some limitations, such as dependence on the Tuya cloud platform and limited hardware support. Therefore, it is recommended to further strengthen the use of local platforms and expand compatibility with various IoT devices.

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From the results of this research, it is possible to draw a conclusion that the implementation of an IoT-based smart energy management system in a university laboratory has provided benefits in optimizing the use of electrical energy efficiently. Recommendations based on the results of this study are to continue to develop the integration of IoT devices, improve communication efficiency and develop local platforms to reduce dependence on cloud platforms.

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