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DEVELOPMENT AND USER ACCEPTANCE EVALUATION OF A LOW-COST IOT-BASED ELECTRICITY MONITORING DASHBOARD FOR HOMES AND SMALL OFFICES

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ABSTRACT

Limited access to integrated, real-time electricity monitoring leaves homeowners and small-office managers with insufficient information to manage electricity consumption effectively. Monthly utility bills provide only a rearview-mirror summary of consumption, making it difficult to identify which appliances, routines, or time-of-day habits are driving costs higher. This study aims to develop and test a low-cost, IoT-based electrical monitoring dashboard for homes and small offices using ESP32 microcontrollers and Home Assistant. The sensor readings are sent wirelessly via Wi-Fi to a locally hosted Home Assistant instance, and a template sensor converts the accumulated kilowatt-hours into a live electricity cost estimate using the Malaysian domestic tariff of RM 0.220 per kWh. The dashboard shows current voltage, current, power consumption and historical consumption graphs. We conducted a User Acceptance Test to assess the proposed system's usability with 50 participants selected through convenience sampling. Moreover, we did not divide participants into groups; all evaluated the same system using the same questionnaire. The results indicated that participants valued the ringgit-based electricity cost information and reported that it helped them better understand their electricity consumption and energy-saving decisions. This study's main contribution is integrating real-time electrical monitoring, historical visualisation, automated cost estimation, and threshold-based notifications into a low-cost, locally hosted dashboard for household and small office users. The evaluation also identified shortcomings in cross-device responsiveness on mobile screens and intermittent dashboard delays when Wi-Fi networks are congested. These areas, along with the requested CSV export feature, guide future development.

Keywords: dashboard; electrical monitoring; ESP32; Home Assistant; Internet of Things

INTRODUCTION

Electricity monitoring is crucial for reducing energy waste, operational costs, and carbon footprints (Billanes et al., 2025), especially as global energy consumption continues to rise. However, consumers in households and small businesses often have limited awareness of how much electricity specific appliances and daily activities consume (Völker et al., 2021). Traditional utility billing provides only a retrospective summary of electricity consumption over a billing period, making it difficult for users to promptly identify daily usage patterns, peak consumption periods, and inefficient appliance use. This limitation can reduce users' ability to take immediate actions to improve energy efficiency (Athanasoulas et al., 2024; Cellina et al., 2024). Previous studies have demonstrated the use of Internet of Things (IoT) technologies and real-time monitoring for energy management; however, an integrated, accessible system that combines real-time electrical measurements, historical consumption visualisation, automated electricity cost estimation, and threshold-based notifications within a single platform remains needed. Limited attention has been given to a low-cost, locally hosted solution that supports both household users and small-office administrators while presenting energy information in a way that non-technical users can understand. The average Malaysian household electricity consumption is estimated to be 300-600kWh/month, which has environmental, economic, and social implications (Ali et al., 2024). Figure 1 shows monthly electricity consumption from 2022 to 2024.

Figure 1

Monthly Electricity Consumption From 2022 to 2024



This alone indicates that many citizens are not fully aware of how to use electricity, which can negatively affect individuals' budgets and the environment. Therefore, this study proposes an IoT-based electrical monitoring dashboard using low-cost ESP32 microcontrollers and Home Assistant to provide continuous monitoring of voltage, current, power consumption, and estimated electricity cost. The system also provides historical data visualisation and notifications when electricity consumption exceeds user-defined limits. This research has two main aims. First, it aims to develop a stable, functional IoT architecture for continuous, non-invasive electrical monitoring in homes and small offices. Second, it aims to evaluate user acceptance of the proposed system through a structured User Acceptance Test (UAT) to assess its usability, functionality, performance, and potential impact on energy-conscious behaviour (Cellina et al., 2024; Paneru et al., 2024).

One of the main challenges is the limited availability of integrated, accessible real-time monitoring solutions that let users analyse their electricity consumption and respond promptly to unusual energy trends. Without them, users cannot monitor their use in real time nor spot unusual energy trends before they become a bigger problem on their energy bill. Therefore, it is necessary to develop an electricity dashboard that provides real-time data and analysis to optimise electricity use. Combined with easy-to-access data visualisation, it can give users actionable insights and a tangible way to improve energy efficiency.

LITERATURE REVIEW

The Internet of Things (IoT) has rapidly changed how homes manage energy through device connectivity, real-time monitoring, and intelligent automation (Al-Ali et al., 2017; Wan Ahmad et al., 2021). With these developments, users can better understand energy consumption and make informed decisions to improve energy efficiency. IoT technologies with low-cost microcontrollers and integrated monitoring systems are increasingly used for real-time electricity monitoring (El-Khozondar et al., 2024; Ismail & Sahari, 2024; Zaidi et al., 2024).

Energy Feedback and Behaviour of the Consumer

Providing consumers with timely, detailed information about their electricity consumption has been shown to encourage energy-saving behaviours. Real-time monitoring lets consumers see how their daily behaviour affects their energy use and check it at any time, rather than waiting for their monthly electricity bill. This information can help users identify inefficient behaviours and make better choices about electricity consumption. Consumers can benefit from direct feedback by monitoring the electricity use of energy-hungry tasks (e.g. air conditioning) and potentially promoting more efficient behaviour. Recent research continues to affirm the importance of energy information being available. Energy-saving applications can affect household energy consumption (Cellina et al., 2024). Useful energy information and user-oriented applications support energy-related practices (Paneru et al., 2024). The studies show that energy monitoring systems should not only collect electricity data but also present it clearly so users can understand and act on their consumption patterns.

IoT Microcontroller Applications in Energy Monitoring

The ESP32 microcontroller has become a popular hardware solution for IoT and smart-home applications due to its reliable performance, low cost, and integrated wireless capabilities (El-Khozondar et al., 2024). Designed by Espressif Systems, the ESP32 is a dual-core processor with low power consumption and integrated Wi-Fi and Bluetooth, enabling it to work with a range of analogue and digital sensors. The ESP32 can also work with non-invasive current sensors, such as split-core Current Transformers (CTs), to monitor electrical current without major changes to a building's electrical installation (El-Khozondar et al., 2024). Moreover, its processing power and wireless connectivity render it suitable for real-time energy monitoring applications.

Recent studies show that ESP32 is well-suited for electricity monitoring. El-Khozondar et al. (2024) proposed a low-cost, IoT-based energy monitoring system using ESP32 to measure voltage, current, active power, and total energy consumption, and to provide real-time information to the user. Zaidi et al. (2024)

proposed a home-based energy monitoring system using an ESP32 and a PZEM-004T V3 module to measure voltage, current, power, energy, frequency, and power factor. The data is presented graphically, and the estimated electricity price is shown on the Blynk platform. Ismail and Sahari (2024) proposed a real-time home energy monitoring system using ESP32, ZMPT101B, and SCT013-030 sensors. They used the ThingSpeak platform to monitor electricity consumption, estimate electricity bills, and detect current spikes.

These studies showed that ESP32-based systems can provide low-cost, real-time electrical monitoring. However, these systems use different platforms and focus on specific functions such as mobile visualisation, bill estimation, or current-spike detection. This highlights the potential to integrate several energy-monitoring functions into a single dashboard, including real-time electrical measurements, historical information, electricity cost estimation, and energy-consumption notifications.

Boards and Home Automation Systems

A central home automation system is required to collect, analyse, and display data produced by sensors connected to the microcontrollers (Wan Ahmad et al., 2021). Home Assistant is another popular open-source choice that emphasises local control and customisation. Users process data locally with a locally hosted platform. This gives users more control over their data than a cloud-based platform. You can also set up dashboards within Home Assistant via YAML files that show your current energy usage, historical trends and calculated information. This makes sensor data more accessible for managing electricity consumption.

Previous studies have also used alternative platforms for energy monitoring. El-Khozondar et al. (2024) received real-time energy information via Blynk and WhatsApp, and Zaidi et al. (2024) received graphical energy monitoring information via Blynk on smartphones and desktop devices. Ismail and Sahari (2024) used ThingSpeak to transmit and visualise real-time residential energy data. These approaches show the potential for remote, real-time monitoring, but they mostly use cloud-based platforms or separate applications for data presentation and notifications.

The literature review shows that previous studies have examined real-time electricity monitoring using IoT technologies. Therefore, the research gap is not a lack of real-time monitoring. Existing studies (El-Khozondar et al., 2024; Ismail & Sahari, 2024; Zaidi et al., 2024) have shown real-time measurement using ESP32-based systems with graphical visualisation, electricity bill estimation, remote monitoring, and abnormal-current detection. However, these functions are typically deployed on different platforms and are focused mainly on individual households or specific monitoring requirements.

However, an integrated, low-cost, locally hosted solution is still needed to provide real-time electrical measurement, historical energy visualisation, automated electricity cost estimation, and threshold-based notifications in a single dashboard. In addition, few systems support household users and small-office administrators while presenting information in an accessible form for non-technical users. The proposed study addresses this gap by integrating ESP32-based electrical monitoring with Home Assistant for real-time monitoring of voltage, current, power, and energy, along with historical data visualisation, estimated electricity costs, and user-defined consumption alerts. This integrated approach provides a simple, practical energy monitoring solution for homes and small offices.

METHODOLOGY

The proposed Home Energy Monitoring System, developed using an IoT approach, was built using the Agile methodology. Agile was chosen for its support of iterative development, continuous testing, and incremental improvement. This approach is common in IoT (Internet of Things) projects because it enables repeated development, testing, and improvement of hardware and software components, resulting in a more reliable, user-friendly system (Guerrero-Ulloa et al., 2023). The development process consisted of four main phases: Planning and Requirement Analysis, System Development, Dashboard Development, and System Evaluation.

Planning and Requirement Analysis

The first step was to define the goals, the functions the proposed system will fulfil, and the required hardware and software. The main goal was to create an IoT-based Home Energy Monitoring system that can measure real-time electrical parameters of houses and visualise them in an interactive dashboard. We chose the ESP32 microcontroller for its Wi-Fi connectivity, low power consumption, and broad compatibility with electrical sensors (Maier et al., 2017). Home Assistant was selected as the data collection system because it allows local data processing, easy dashboard configuration, and easy integration with ESPHome devices.

System Development

The team developed the hardware and software components incrementally using Agile methodology. The hardware layer comprised an ESP32 microcontroller board and current and voltage measuring sensors used to gather real-time electrical measurements (Maier et al., 2017).

ESPHome was used to program the ESP32, allowing ESP devices to be programmed using YAML files and seamlessly integrated with Home Assistant. For each development iteration, we tested communication between the sensor, ESP32, and Home Assistant server to ensure stable data transmission across the local Wi-Fi network. We fixed any problems found during testing, such as communication instability or sensor calibration issues, before moving to the next iteration.

The sensors were calibrated to improve the accuracy of voltage (V), current (A), and active power (W) measurements before deploying the system for evaluation. Figure 2 shows the proposed system's hardware configuration.

Figure 2

Hardware Configuration of the Proposed IoT-Based Home Energy Monitoring System



Dashboard Development

The team built the software interface using Home Assistant, installed locally on a dedicated server as the central monitoring system. Over several iterations, the team refined the dashboard throughout the Agile development process to make it easier to use, more useful, and more visually appealing for displaying electrical data.

The dashboard displays real-time voltage, current, active power, and accumulated energy consumption. Historical graphs also show daily, weekly, and monthly electricity consumption. We also developed a live electricity cost estimator using a Home Assistant template sensor. The system automatically estimates electricity cost based on energy consumption in kilowatt-hours (kWh) and the RM 0.220/kWh domestic electricity tariff (Suruhanjaya Tenaga, 2023). Each development cycle informed adjustments to the dashboard layout, graphical display, and sensor update frequency to improve system performance and user experience. Figure 3 shows the resulting Home Assistant dashboard.

Figure 3

Home Assistant Dashboard Displaying Real-Time Electrical Measurements and Estimated Electricity Costs



System Evaluation

After development, the system underwent a User Acceptance Test (UAT) to assess usability. Participants included university students, members of the public, and homeowners recruited through convenience sampling, for a total of 50 participants. Participants interacted with the physical devices and the Home Assistant interface, switching different electric appliances on and off while monitoring changes in voltage, current, power consumption, and estimated electricity cost on the interface. After the testing session, participants completed a structured questionnaire via Google Forms. The questionnaire covered four components of the proposed system: usability, functionality, system performance, and impact and practicality. Responses were evaluated on a basic five-point Likert scale from 1 = Strongly Disagree to 5 = Strongly Agree. The responses were analysed using descriptive statistics to determine overall user acceptance and assess whether the proposed system meets the desired objectives.

RESULT AND DISCUSSION

The UAT results show generally positive user acceptance of the proposed IoT monitoring system. A total of 50 participants completed the evaluation. The descriptive statistics are presented in four main sections.

Usability (Interface & Accessibility)

Usability scores for the dashboard interface are given in Table 1. The UAT results indicate that the dashboard's visual design is quite good, with the clean, uncluttered layout receiving the highest scores in the Usability category (Mean = 3.52). Users can also easily navigate between real-time and historical data (Mean = 3.40). However, the units of the Home Assistant interface were rated lower (Mean = 3.04), indicating room for CSS optimisation to scale elements appropriately on smaller mobile screens.

Table 1

Usability (Interface & Accessibility)

Question	Mean	SD
The layout of the dashboard is clean, and the information is not cluttered.	3.52	1.23
I can easily navigate between the real-time overview and the historical data sections.	3.40	1.20
The dashboard interface is straightforward and user-friendly.	3.34	1.17
The system is easy to access and works well across all my devices.	3.04	1.43
Group Mean	3.33	

Note. $N = 50$. Items were rated on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree).

Functionality and Visualisation

Table 2 reports scores for the system's core functionality. Users strongly agreed that real-time measurement of voltage, current, and electricity consumption is convenient (Mean = 3.41). They also rated the ability to store and review historical data quite well (Mean = 3.34), indicating that the Home Assistant database's data logging feature works as expected. In this category, Interactive chart clarity scored the lowest, with opportunities to improve chart labelling and interactivity.

Table 2

Functionality and Visualisation

Question	Mean	SD
I can easily track my real-time voltage, current, and overall power consumption.	3.41	1.24
The system successfully stores my historical data, making it easy to review past energy consumption.	3.34	1.29
The historical data charts allow me to compare my daily, weekly, or monthly usage easily.	3.24	1.29
The interactive charts provide clear and understandable visualisations of my electricity data.	3.20	1.28
Group Mean	3.30	

Note. $N = 50$. Items were rated on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree).

System Performance (Speed & Stability)

The system's technical performance was rated moderate to high, as shown in Table 3. Users rated clear, timely delivery of notifications when electricity use exceeded the set limits as the best-performing feature (Mean = 3.30). The web dashboard scored lowest in this group (Mean = 3.08), suggesting that minor latency/buffering problems likely depend on the strength of the user's local Wi-Fi network. The results indicate scope to optimise server response time and use a local caching mechanism in future versions.

Table 3

System Performance (Speed & Stability)

Question	Mean	SD
I receive clear and timely notifications when my electricity usage exceeds predefined limits.	3.30	1.22
The energy readings update quickly and consistently on the dashboard without noticeable delay.	3.24	1.30
It is easy to adjust or configure the custom usage limit that triggers my warning notifications.	3.22	1.42
The web dashboard remains stable and responsive during the monitoring sessions.	3.08	1.32
Group Mean	3.21	

Note. $N = 50$. Items were rated on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree).

Impact and Practicality

The largest differences were in the Impact & Practicality category, as shown in Table 4. The cost transparency of the system was appreciated by the participants as the most important individual item in the entire survey (Mean = 3.54) due to the transparency of the estimated expenses based on the RM 0.220 per kWh tariff. In addition, energy reduction on the dashboard was highly believed by users (Mean = 3.48) and that the dashboard helped them make decisions about energy efficiency (Mean = 3.40). The lowest result in this group (Mean = 3.10) was for the motivational element of turning off unused appliances, indicating that more salient real-time alerts and/or gamification elements may further improve the behavioural impact.

Table 4

Impact and Practicality

Question	Mean	SD
The dashboard gives me a clear understanding of estimated expenses based on the RM 0.220 per kWh tariff calculation.	3.54	1.34
I noticed a clear reduction in my energy usage after implementing and following the dashboard's insights.	3.48	1.22
The information provided helps me make better decisions to improve energy efficiency.	3.40	1.25
The system helps me easily detect abnormal energy patterns or identify high-use areas.	3.32	1.32
Using this dashboard makes me more aware of my daily electricity usage.	3.16	1.27
The dashboard helps me better understand how my personal electricity consumption impacts the environment and carbon emissions.	3.12	1.21
Using this system actively motivates me to turn off unused electrical appliances to save energy.	3.10	1.28
Group Mean	3.30	

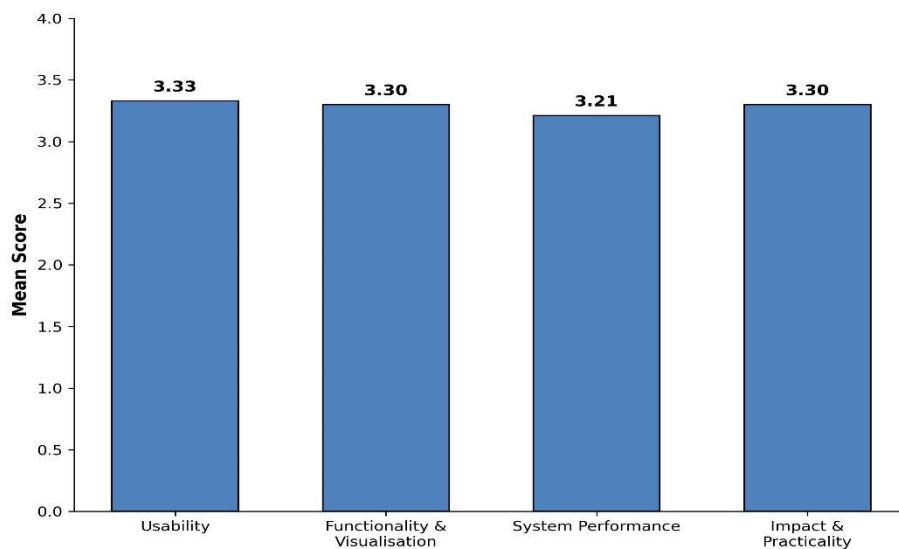
Note. $N = 50$. Items were rated on a 5-point Likert scale (1 = strongly disagree, 5 = strongly agree).

Summary of Evaluation Categories

A comparison of mean scores across the four primary evaluation categories shows that Usability had the highest group mean (3.33), followed by Functionality and Visualisation and Impact and Practicality, both of which recorded a group mean of 3.30. System Performance had the lowest group mean (3.21). These results indicate that participants generally accepted the proposed system, while system performance remains an area for further improvement. Figure 4 compares the group means of the four categories.

Figure 4

Mean Scores Across the Four Primary Evaluation Categories



Note. $N = 50$.

Qualitative Feedback Analysis

The open-ended feedback section yielded extremely positive responses from most respondents (43 out of 50) who left the field blank or who specifically stated "None" or "All good". The 7 participants who gave qualitative feedback identified areas for further development. There were several requests for adding historical data export features (e.g. "boleh export data" and "TAMBAH HISTORY FEATURES"). In addition, users called for "more advanced, actionable guidance such as tips on how to reduce the energy usage", and "AI features", such as predictive consumption analysis, to be added to the application.

CONCLUSION

The results showed that the proposed IoT-based Electrical Monitoring Dashboard, using an ESP32 microcontroller and the Home Assistant platform, was technically feasible and well accepted by users. However, the most important feature of the system (Mean = 3.54) was integrating raw wattage data with automated financial estimates based on the local RM 0.220 per kWh tariff.

Its clean visual layout, practical insights and cost transparency were highlighted as key strengths. The evaluation showed that the prototype is well prepared for small-scale deployment, but it has minor technical areas for improvement. Future iterations will focus on improving the Home Assistant UI/UX responsiveness across devices, improving local server stability to reduce network latency, and adding requested features such as CSV data export and AI-based predictive consumption analysis. To summarise, this system is a useful, low-cost way to link passive energy use with active sustainable energy management.

The prototype has shown strong readiness for small-scale deployment, but the evaluation revealed technical areas that need further development. Overall, cross-device accessibility scored lowest (Mean = 3.04), highlighting the need to optimise the CSS further to keep dashboard elements consistently visible and accessible on mobile devices, tablets, and desktops. Dashboard stability (Mean = 3.08) was the second area participants highlighted. For future work, we will focus on server-side response optimisation, local caching, and stable IoT communication to ensure smooth data transmission and system performance, especially during high network traffic.

We will consider these findings in future iterations and add the features participants most requested in the open-ended feedback. We will add a historical data export feature using CSV to enable users to download, store, and analyse their electricity consumption data outside the dashboard. The system will also investigate incorporating artificial intelligence (AI) predictive analysis to provide electricity usage predictions, so users can better forecast energy use instead of relying only on past patterns.

The dashboard will also be improved to let users define monitoring and billing periods based on their needs, rather than a fixed monthly cycle. This feature will give users more flexibility to view electricity consumption in custom periods, such as weekly, biweekly, or other user-defined intervals. The system will also include a pop-up notification feature to alert users in real time when electricity usage exceeds the predefined amount for the chosen monitoring period. This will enable users to act in real time to avoid exceeding their allotted usage or consuming excess energy.

Finally, the project will offer more personalised, actionable recommendations, such as automatic energy-saving tips based on users' consumption patterns. These improvements will upgrade the system from a monitoring system to an intelligent energy management system that can actively help users change their energy consumption patterns toward more efficient, sustainable use.

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