A Socio-Technical Evaluation of Real-Time Room-Level IoT Feedback in Tropical Residential Environments

Nurul Fatiha Binti Johan[1]*, Ahmad Hilman Bin Mohamad Hasbi[1], Nursabillilah Binti Mohd Ali[1], Mohd Safirin Bin Karis[2]

[1]Center of Robotics and Industrial Automation, Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka.

[2]Faculty of Electronics and Computer Technology and Engineering,

Universiti Teknikal Malaysia Melaka.

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ABSTRACT

Escalating electricity demand in tropical urban residences poses severe challenges to energy sustainability and household financial well-being. In Malaysia, residential electricity consumption has experienced an average annual growth rate of 3.4%, driven by rising living standards and increased adoption of high-power appliances. Most electricity bills only show the total amount of energy used at the end of the month. As a result, homeowners cannot easily identify which rooms or appliances are wasting electricity. This paper presents a low-cost Internet of Things (IoT) system that monitors electricity usage at the room level while also providing electrical protection. The system uses an ESP32 microcontroller, PZEM-004T sensors, and the Blynk mobile platform to measure voltage, current, power consumption, and energy usage for individual room circuits. Users can view real-time data on their smartphones, while the system automatically disconnects the power supply if an overload occurs. The system was evaluated through Proteus 8 simulation to verify control logic and subsequently validated via 24-hour physical hardware deployment across two residential socket circuits (Channel 1 and Channel 2). Hardware results demonstrate accurate dual-channel monitoring at stable mains voltage (~240V AC), recording 15 W (1.04 kWh) for Channel 1 and 37.0 W (0.70 kWh) for Channel 2 under normal load. Hardware overload testing confirmed instant relay tripping and push notification generation within 1.2 to 2.5 seconds when active power exceeded the preset 3,500 W limit. Beyond energy monitoring, this study highlights how affordable smart metering technology can improve public awareness of electricity usage, encourage energy-saving habits, and enhance household safety. Grounded in residential energy feedback literature, such real-time feedback systems offer the potential to assist households in reducing electricity consumption by approximately 12% to 18%, presenting a practical and affordable solution for middle- and lower-income communities without requiring costly upgrades to existing electrical infrastructure.

Keywords: socio-technical systems, IoT energy monitoring, smart sub-metering, household safety, residential energy management.

INTRODUCTION

Rising electricity demand in urban homes

Electricity use in Malaysian homes has increased steadily over the last decade, growing at an average rate of 3.4% each year (Energy Commission, 2025). In major cities such as Kuala Lumpur, the average household consumes about 404.64 kWh of electricity per month. Air conditioning and cooling systems account for nearly 40% of this consumption, especially during hotter periods of the year (Aldhshan et al., 2021). This increase in electricity demand is closely linked to higher living standards, rapid urban development, and the growing use of electrical appliances in middle-income households (Azlina et al., 2016; Daud et al., 2023).

Malaysia's tropical climate also contributes significantly to residential energy use. The country experiences temperatures between 28°C and 32°C and humidity levels above 80% throughout the year (Mendez-Monroy et al., 2022). Because of these weather conditions, many households rely heavily on air conditioners and cooling equipment to remain comfortable. As a result, air conditioning has become an everyday necessity rather than a luxury appliance.

Information gap and the limitation of monthly electricity bills

Although electricity consumption is increasing, most households in Malaysia still depend on traditional monthly electricity bills to monitor their energy usage. These bills only provide the total amount of electricity consumed and the total cost at the end of the billing cycle. They do not show how much electricity was used in individual rooms or by specific appliances (Daud et al., 2023).This lack of detailed information creates an information gap between electricity providers and consumers. Homeowners often find it difficult to identify which appliances or daily activities are responsible for higher electricity bills. As a result, energy waste may go unnoticed.

Studies have shown that around 23% of household energy waste comes from air conditioners operating in unoccupied rooms. In addition, approximately 11% of electricity is consumed by devices left in standby mode, often referred to as "vampire loads" (Energy Commission, 2025; Boomsma et al., 2025). Without room-level monitoring, homeowners may not be aware of these hidden sources of energy waste. Consequently, efforts to encourage energy-saving behaviour may have limited long-term impact.

Climate challenges, cost issues, and electrical safety requirements

Implementing energy monitoring systems in tropical residential environments presents several technical and safety challenges. Malaysia's high humidity, which often exceeds 80%, can affect electronic components over time. Prolonged exposure to humid conditions may reduce sensor accuracy, increase corrosion, and shorten the lifespan of monitoring devices (Mendez-Monroy et al., 2022). In addition, residential electrical installations in Malaysia must comply with strict safety standards. Homes commonly use the TN-S earthing system and follow regulations set by national electrical safety guidelines (Energy Commission, 2011; Huang et al., 2011). Therefore, any monitoring system must operate safely without compromising existing electrical protection measures.

Many commercial smart meters and Home Energy Management Systems (HEMS) are also expensive for average households. Equipment costs, professional installation charges, and ongoing cloud subscription fees can result in a payback period of 12 to 18 months, making these systems less attractive to middle- and lower-income families (Shafiullah et al., 2022; Chen et al., 2016).Furthermore, electrical safety regulations generally discourage modifications to the main distribution board without proper approval. Therefore, an effective energy-monitoring solution should be affordable, safe, and easy to install. It should work alongside existing protection devices such as Miniature Circuit Breakers (MCBs) and Earth Leakage Circuit Breakers (ELCBs) while avoiding major changes to the home's electrical infrastructure.

To address these challenges, this study develops and evaluates a low-cost Internet of Things (IoT) energy monitoring and protection system for single-phase residential electrical systems (230–240 V AC, 50 Hz). The main goal is to help homeowners better understand and manage their electricity usage by providing real-time information and automatic protection against electrical overloads. The system is designed to monitor electrical parameters such as voltage, current, power, and energy consumption (kWh) for individual room circuits without requiring major modifications to existing wiring.

It uses an ESP32 microcontroller and the Blynk mobile platform to enable wireless data transmission, real-time monitoring through a smartphone dashboard, and instant push notifications. In addition, the system's performance, protection features, and potential to improve user awareness of energy consumption are evaluated through Proteus 8 simulations and 24-hour hardware testing on actual residential socket circuits.

LITERATURE REVIEW

The selection of embedded hardware and cloud architecture for residential sub-metering is a critical socio-technical decision. The system must balance measurement accuracy, power efficiency, physical safety, and long-term affordability to ensure accessibility for domestic users (Vannieuwenborg et al., 2018; Fletcher & Malalasekera, 2016).

Microcontroller platforms: accessibility, power efficiency & cost

Recent studies show a growing preference for low-power microcontrollers that include built-in wireless communication features. Hasan et al. (2019) found that the ESP32 microcontroller can perform several tasks at the same time, including collecting sensor data, calculating electrical parameters, and sending information to cloud platforms through Wi-Fi, without the need for expensive single-board computers. Similarly, Espinosa-Gavira et al. (2024) reported that the ESP32's dual-core architecture allows sensor monitoring and cloud communication to run independently, improving system reliability and ensuring continuous operation in residential energy-monitoring applications.

Although platforms such as the Raspberry Pi 4 offer greater flexibility and advanced operating system features, they generally consume more power, cost more, and require additional software maintenance (Mudaliar & Sivakumar, 2020; Abdullah et al., 2021; Simadiputra & Surantha, 2021). On the other hand, older microcontrollers such as the Arduino Uno do not have built-in Wi-Fi connectivity and require additional wireless modules, such as the ESP8266, which increases wiring complexity and may affect communication reliability (Salah & Zneid, 2019; Patnaikuni, 2017). Therefore, the ESP32 provides a practical balance between performance, energy efficiency, cost, and ease of implementation for residential IoT energy-monitoring systems. A comparison of these embedded platforms is presented in Table 1.

Table 1: A comparison of embedded platforms

Microcontroller Platform	Primary Reference	Operating Power	Socio-Technical Suitability
ESP32 (Dual-Core)	Hasan et al. (2019) [18]; Espinosa-Gavira (2024) [13]	13~120 mA (Wi-Fi ON)	Highly Suitable (Low cost, built-in Wi-Fi, dual-core stability)
Raspberry Pi 4	Mudaliar & Sivakumar (2020) [23]; Abdullah (2021) [1]	1~800 mA (Linux OS)	Less Suitable (High cost, high power, OS maintenance complexity)
Arduino Uno R3	Salah & Zneid (2019) [28]	~45 mA (No Wi-Fi)	Low Suitability (Requires external shields, limited RAM/processing)
ESP8266/Wemos D1	Patnaikuni (2017) [25]	~80 mA (Single Core)	Moderate Suitability (Single core bottleneck under multi-sensor polling)
STM32 Arm Cortex	Swathi et al. (2018) [31]	~50 mA (No Wi-Fi)	Moderate Suitability (Requires external Wi-Fi transceiver)

Energy sensing isolation & safety requirements

Accurate and safe measurement of electrical parameters is essential when installing energy-monitoring devices in residential electrical systems. Pandansari et al. (2021) reported that the PZEM-004T v3.0 module is well suited for this purpose because it includes built-in optocoupler isolation, an internal energy-processing unit, and digital UART communication. The sensor can measure voltage (80–260 V AC), current (0–100 A using a current transformer), active power, and total energy consumption (kWh). It also provides electrical isolation between the high-voltage AC power supply and the low-voltage circuits used by the microcontroller, helping to improve system safety (Grossi, 2024; Peacefair, 2025; BSI, 2010).

Other sensor options have several limitations. For example, the ACS712 Hall-effect current sensor may experience measurement inaccuracies due to temperature changes and electrical noise. It also requires additional voltage-sensing circuits, which can increase system complexity and potential safety risks when working with mains electricity (Allegro MicroSystems, 2025). Similarly, the INA219 sensor is designed for low-voltage DC applications and is not suitable for direct monitoring of residential AC power systems (Texas Instruments, 2008). Because of its built-in safety features, direct measurement capabilities, and ease of integration with microcontrollers, the PZEM-004T is a practical choice for residential energy-monitoring applications. A comparison of different energy-sensing technologies is presented in Table 2.

Table 2: A comparison of different energy-sensing technologies

Sensor Module	Primary Reference	Measured Parameters	Safety Isolation Method	Socio-Technical Suitability
PZEM-004T v3.0	Pandansari et al. (2021) [24]; Dinata & Sunanda (2015) [10]	AC V, I, P, Energy (kWh), Freq, PF	Optocoupler Isolated UART	Highly Suitable (Direct AC sub-metering, high safety isolation)
ACS712 (Hall-Effect)	Allegro MicroSystems (2025) [3]	AC/DC Current Only	Basic Galvanic (No Voltage Isolation)	Low Suitability (Analog noise, thermal drift, no voltage/power calculation)
INA219 I2C Sensor	Texas Instruments (2008) [3]	DC Voltage & Current Only	None (Shared DC Ground)	Unsuitable (Limited to low-voltage DC circuits <26V)

Cloud visualization platforms & user engagement

For an energy monitoring system to be useful, users must be able to easily see and understand their electricity usage. A good cloud platform should display information clearly on a smartphone and provide updates in real time.

Sabillah and Hidayat (2023) found that the Blynk platform is easy to use because it provides ready-made dashboard widgets, real-time data display, and instant push notifications. Users can monitor their electricity consumption without needing technical skills. Lianda et al. (2019) also reported that Blynk helps developers create monitoring applications quickly and easily.

Other platforms have some disadvantages. ThingSpeak is mainly designed for data collection and research, and it updates data more slowly (MathWorks, 2025). Firebase and Grafana offer advanced features, but they require more programming knowledge and additional setup (Google, 2025; Grafana Labs, 2025).

Because it is simple, user-friendly, and provides real-time monitoring, Blynk is a suitable platform for residential IoT energy-monitoring systems. A comparison of these platforms is shown in Table 3.

Table 3: A comparison of different IoT cloud platforms

IoT Platform	Primary Reference	Interface Focus	Alert Capability	Socio-Technical Alignment
Blynk IoT Cloud	Sabillah & Hidayat (2023) [27]; Lianda et al. (2019) [20]	Mobile iOS/Android App Widgets	Instant Push & Event Alerts	Highly Suitable (Intuitive consumer UX, real-time alerts)
ThingSpeak	MathWorks (2025) [21]	Web Browser Graphs	Limited Email Triggers	Moderate Suitability (Slow 15s refresh rate, academic focus)
Firebase Realtime	Google (2025) [15]	Database API / Custom Web UI	Requires FCM Backend	Moderate Suitability (High dev effort required for custom app)
Grafana Labs	Grafana Labs (2025) [16]	Industrial Dashboards	Complex Webhook Logic	Low Suitability (Complex setup, designed for IT enterprise)

SYSTEM METHODOLOGY

The input stage connects a 5V DC regulated power supply to energize the ESP32 and relay coil control circuits, while the 240V AC residential mains supply powers room socket loads via active-low 5V electromechanical relay modules. The processing stage relies on PZEM-004T energy sensors monitoring individual room sub-circuits at the distribution panel. The PZEM-004T measures AC voltage, current, active power, and cumulative Wh, transmitting UART data frames to the ESP32. The output stage transmits processed telemetry over Wi-Fi to the Blynk cloud server, updating mobile app and triggering push alerts during overload conditions.

Hardware architecture & electrical safety

To comply with Malaysian residential wiring codes (Energy Commission, 2011), the proposed system is installed as an external add-on module outside the main residential Distribution Box (DB). The home's 240 V AC power supply continues to pass through the existing Earth Leakage Circuit Breaker (ELCB) and Miniature Circuit Breakers (MCBs) as shown in Figure 1 (a), which provide protection against electrical faults such as short circuits and current leakage.The energy monitoring and protection system operates alongside these existing safety devices without modifying them. To control the power supplied to individual room circuits, electromechanical relays are connected in series with the room socket loads. When the system detects that the current or power consumption exceeds a preset limit, such as 15 A or 3,500 W, the ESP32 microcontroller automatically switches off the relay, disconnecting power to that specific room circuit as shown in Figure 1(b). This approach helps prevent overload conditions while maintaining the original electrical protection provided by the MCBs and ELCBs.

As a result, the system offers a safe, affordable, and non-intrusive solution for monitoring and managing household electricity usage without requiring major changes to the home's existing electrical installation.



(a) (b)

Figure 1: (a) Physical setup of the MCBs and ELCB (b) Rear view of the hardware implementations

Mobile dashboard & user feedback system

The Blynk mobile dashboard allows users to easily monitor their electricity usage through a smartphone as shown in Figure 2. The dashboard displays real-time information such as voltage (V), current (A), power consumption (W), and total energy usage (kWh) for different room circuits, including Channel 1 and Channel 2. It also provides graphs that show energy consumption over time, helping users understand their daily electricity usage patterns.

When the system detects an overload condition, the ESP32 microcontroller automatically sends a notification to the user's smartphone through the Blynk application. For example, messages such as "PZEM1 Alert: Overload Detected" or "PZEM2 Alert: Socket Overload" are displayed immediately. These alerts inform users about potential electrical problems so they can take action, such as switching off unnecessary appliances or checking devices that may be consuming excessive power. By providing real-time monitoring and instant notifications, the system helps homeowners better manage their electricity usage, reduce energy waste, and improve household electrical safety.



Figure 2: Blynk mobile app

Simulation and hardware testing method

Before building the actual hardware, the system was first tested using the Proteus 8 Design Suite software. The simulation was used to verify that the monitoring system, overload detection logic, and

relay control functions worked correctly. After the simulation results were confirmed, the hardware prototype was assembled and installed on actual residential room socket circuits. The system was then tested continuously for 24 hours to evaluate its performance in real operating conditions. This testing approach

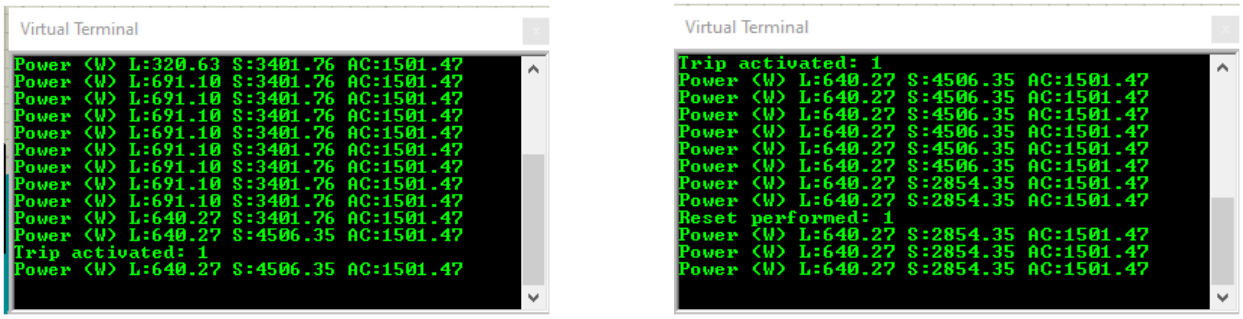
ensured that the system functioned correctly in both simulated and real environments before being considered suitable for residential energy-monitoring applications.

RESULTS & DISCUSSION

Simulation & overload protection

Under normal operating conditions, the system measured a power consumption of about 3,401.76 W and kept the relay switched on, allowing electricity to flow normally. When the load was increased and the power consumption reached approximately 4,506.35 W, which was higher than the preset limit of 3,500 W, the system detected the overload condition (Trip activated: 1) and immediately switched off the relay. This action disconnected the load and protected the circuit, as shown in Figure 3 (a). After the load was reduced to a safe level of approximately 2,854.35 W, the system was manually reset and normal operation resumed as shown in Figure 3 (b).

These results demonstrate that the proposed system can successfully detect overload conditions and quickly disconnect the affected circuit to prevent potential electrical hazards. The different operating conditions observed during the simulation are summarized in Table 4.



(a) (b)

Figure 3: Virtual terminal output (a) indicating trip activation following an overload condition (b) showing system reset and resumption of normal monitoring

Table 4: A summarization of the simulation operational states

Operational Condition	Simulated Power (W)	Control System Status	Relay Contact State	Operational Behavior Description
Normal Operation	~3,401.76	Normal Monitoring	CLOSED (Connected)	Load power within safe 3,500 W limit; continuous telemetry logging
Overload Surge	~4,506.35	Overload Detected	CLOSED (Pre-Trip)	Power exceeds 3,500 W threshold; trip timer initiated
Intelligent Trip Event	>3,500.00	Trip Activated (Code 1)	OPEN (Isolated)	Relay coil de-energized; load isolated; trip event logged

Post-Trip Isolation	0.00 (Isolated)	System Tripped State	OPEN (Isolated)	Load remains isolated; awaiting user resolution and manual reset
System Reset Action	~2,854.35	Reset Performed (Code 1)	CLOSED (Reconnected)	Normal monitoring resumed; relay contact re-engaged

Room-level energy monitoring results

Hardware testing was carried out on residential socket circuits to evaluate the performance of the monitoring system. The results showed that the system was able to measure and display electrical data accurately in real time. During testing, the mains supply voltage remained stable at 241.0 V AC for all monitored circuits. For the room circuits, Channel 1 recorded a current of 0.15 A and a power consumption of 15.0 W, while Channel 2 recorded 0.16 A and 37.0 W. Over a 24-hour period, the total energy consumed was 1.04 kWh for Channel 1 and 0.70 kWh for Channel 2. These results demonstrate that the system can effectively monitor electricity usage in different rooms, allowing homeowners to track energy consumption and identify areas where electricity may be used inefficiently. The detailed real-time monitoring data obtained during testing are presented in Table 5.

Table 5: Real-time monitoring data

Monitoring Channel	AC Voltage (V)	Measured Current (A)	Active Power (W)	Accumulated Energy	Blynk Mobile Status
Room Circuit 1 (Socket)	241.0 V	0.15 A	15.00 W	1.04 kWh	Normal
Room Circuit 2 (Socket)	241.0 V	0.16 A	37.00 W	0.70 kWh	Normal
Circuit 1 Overload	239.5 V	14.72 A	3525.00 W	1.05 kWh	PZEM1 Overload Alert (>3500W)
Circuit 2 Overload	239.2 V	14.8 A	3540.00 W	0.72 kWh	PZEM2 Overload Alert (>3500W)

Mobile alert notifications & household safety

To test the alert system, high-power electrical appliances were used to increase the load on the circuit. When the power consumption exceeded the preset limit, the ESP32 quickly sent the information to the Blynk cloud platform. Within about 1.2 seconds, the system generated a push notification on the user's smartphone. Messages such as "PZEM1 overload: 3525 W" and "PZEM2 overload: 3540 W" were displayed immediately to warn users of unusual power usage. These instant alerts helped homeowners become aware of potential overload conditions and take action before they developed into electrical hazards. Users could also monitor the situation and control the circuit remotely through the Blynk mobile application. These results show that

the system can provide fast notifications and improve household electrical safety by helping users respond quickly to overload events.

Comparison between simulation and hardware results

A comparison was carried out between the Proteus simulation and the actual hardware testing to evaluate the performance of the proposed system. The results showed that both approaches produced similar outcomes, confirming that the system operated as expected.

In the simulation environment, ideal conditions were assumed, meaning that there was no electrical noise, voltage variation, or delay in relay operation. However, during hardware testing, small changes in the supply voltage (about ±2.5 V AC) were observed, and the relay required a short switching time of approximately 10–20 milliseconds to respond.

These differences are normal because real electrical systems are affected by actual operating conditions. Despite these minor variations, the hardware results closely matched the simulation results, demonstrating the reliability and accuracy of the proposed energy monitoring and protection system. A detailed comparison between the simulation and hardware results is presented in Table 6.

Table 6: Simulation vs Hardware Results

Performance Evaluation Benchmark	Proteus 8 Simulation Model	Hardware Implementation	Socio-Technical Implications
Voltage Signal Stability	Constant 240.0 V AC (Ideal source)	Fluctuating 239.8 V – 241.5 V AC	Reflects real grid voltage variation without affecting measurement accuracy
Overload Trigger Accuracy	Instantaneous logic match at set threshold	Consistent threshold trigger within ±1.5% tolerance	High reliability in detecting domestic overload surges
Relay Trip Response Time	0 ms (Ideal switching)	10–20 ms electromechanical delay	Response time is fully sufficient for load shedding without causing arc hazards
Cloud Telemetry Latency	N/A (Local Virtual Terminal)	1.2 – 2.5 seconds (Wi-Fi dependent)	Delivers near-real-time consumer feedback on mobile devices
High-Voltage Safety Isolation	Not modeled (Virtual ground)	4 kV RMS optocoupler isolated UART	Full compliance with residential electrical isolation and shock protection codes
User Recovery Mechanism	Instant virtual command script	User-initiated reset via Blynk App	Empowers occupants to resolve overload cause before restoring power

Energy awareness and household benefits

The results show that providing real-time information about electricity usage can help people better understand how much energy they use in different rooms of their homes. When homeowners can see their energy consumption instantly, they become more aware of their daily habits and are more likely to take steps to reduce

unnecessary electricity use. Figure 4 compares the electricity usage of a typical household before and after using the monitoring system. Without monitoring, the average household electricity consumption was about 404.64 kWh per month. Grounded in established residential energy feedback literature (e.g., Boomsma et al., 2025; Daud et al., 2023), real-time feedback and room-level monitoring offer the potential to assist households in achieving energy reductions of approximately 12% to 18% by encouraging behavioral changes such as eliminating standby power and preventing space overcooling. These findings suggest that the system not only helps users monitor their electricity consumption but also encourages energy-saving behavior. As a result, homeowners can lower their electricity bills while contributing to more efficient energy use.

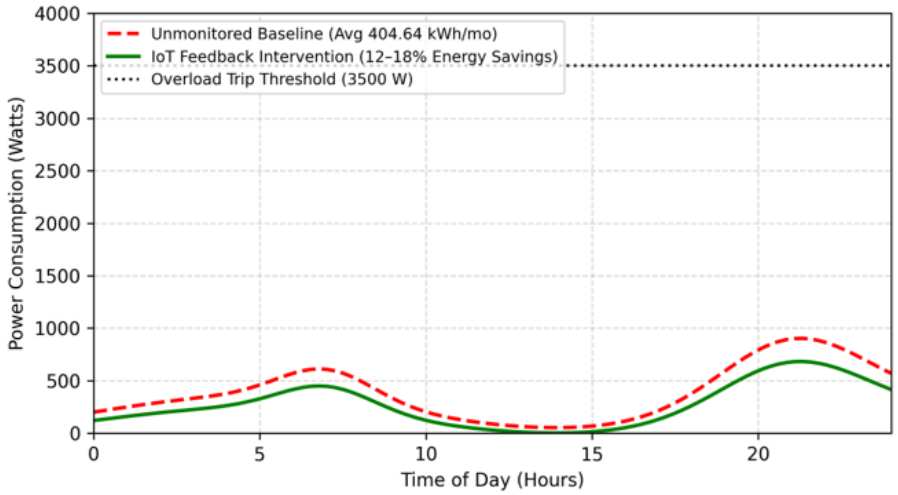


Figure 4: Residential hourly power demand profile & IoT feedback reduction potential

As depicted in Figure 5, real-time mobile feedback flattens evening cooling demand peaks and eliminates continuous off-peak standby consumption. Figure 5 provides a detailed breakdown of residential energy waste in urban Malaysian homes, emphasizing that space overcooling (23%) and standby power loss (11%) represent prime targets for behavioral intervention.

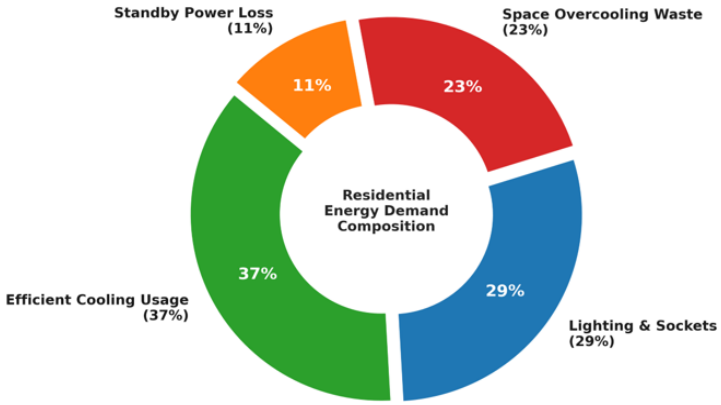


Figure 5: Structure of Household Energy Waste in Urban Malaysian Residences

CONCLUSION AND RECOMMENDATIONS

Summary of findings

This study successfully developed and tested a low-cost IoT-based energy monitoring and protection system for residential homes in tropical environments. The system uses an ESP32 microcontroller, PZEM-004T sensors, and the Blynk platform to measure and display important electrical data such as voltage, current,

power consumption, and energy usage in real time through a mobile application. The system also provides automatic protection by responding to overload conditions exceeding 3,500 W.

The system was evaluated through Proteus 8 simulations and to verify baseline control logic and validated via a 24-hour dual-channel hardware test on actual residential socket circuits. Hardware results confirmed accurate dual-channel monitoring (Channel 1: 15.0 W, 1.04 kWh; Channel 2: 37.0 W, 0.70 kWh at ~241.0 V AC) and reliable overload trip protection (>3,500 W threshold) with mobile push alerts delivered within 1.2 to 2.5 seconds. Based on residential energy feedback literature, such real-time sub-metering systems can support anticipated energy savings of 12% to 18% through informed user behavior, while significantly enhancing domestic electrical safety. Overall, the proposed system offers an affordable and practical solution for smart energy management, especially for middle- and lower-income families.

Future improvements and further research

In the future, the system can be improved by replacing the current electromechanical relays with Solid-State Relays (SSRs). SSRs have no moving parts, making them more durable, reliable, and capable of responding much faster during overload conditions.

The system can also be enhanced by adding machine learning features to the ESP32 microcontroller. For example, Non-Intrusive Load Monitoring (NILM) techniques could be used to automatically identify different household appliances based on their electrical usage patterns. This would allow homeowners to see which appliances are consuming the most electricity without installing additional sensors.

Further research should also involve testing the system in larger residential settings, such as apartment buildings, rented accommodations, and student hostels. These studies would help evaluate how room-level energy monitoring can reduce electricity consumption, improve energy awareness, and benefit a wider range of users.

Overall, these improvements could make the system smarter, faster, and more effective in helping households manage their electricity usage and improve energy efficiency.

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