BRIDGE: The Multidisciplinary Research Portal
Vol. 3, No. 1 (2025), pp. 243-251 | p-ISSN: 3025-6585, e-ISSN: 3025-3640
https://jurnal.sttnlampung.ac.id/index.php/bridge

IoT-Based Real-Time Monitoring and Energy Consumption Analysis for Residential Electrical Systems

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Article History: Received: December, 12th 2025; Accepted: January, 19st 2025; Published: January, 31th 2025

ABSTRACT

The growing demand for efficient and transparent household energy management has increased the need for accurate, real-time electricity monitoring systems. This study presents the design, implementation, and experimental validation of an Internet of Things (IoT)-based system for real-time monitoring and analysis of residential electrical energy consumption. The proposed system integrates voltage and current sensing with wireless data transmission to measure voltage, current, instantaneous power, energy consumption (kWh), power factor, and electricity cost estimation, with data displayed locally and remotely through a cloud-based platform. An experimental methodology was employed to evaluate system performance using various household appliances representing resistive and inductive loads. Measurement accuracy was assessed by comparison with calibrated reference instruments, yielding an average voltage error of 0.30% and current error of 0.28%, indicating high precision suitable for residential applications. The results reveal significant variation in energy consumption across appliances, highlighting inefficient loads with disproportionate energy usage. The system demonstrates stable data synchronization between local and remote interfaces with acceptable transmission latency, and incorporates automated load control to support demand-side energy management. This study contributes to the field of smart energy systems by providing a cost-effective, accurate, and scalable IoT-based solution for appliance-level energy monitoring and consumption analysis. The proposed approach offers practical insights for data-driven energy conservation, supports predictive energy management strategies, and aligns with global efforts toward sustainable and intelligent residential power systems.

Keywords: *internet of things; real-time energy monitoring; residential electrical systems; energy consumption analysis; smart energy management*

INTRODUCTION

The rapid advancement of digital technologies, particularly the Internet of Things (IoT), has transformed multiple sectors, including energy management in residential environments. IoT enables the collection, transmission, and analysis of household electricity consumption data in real time, offering substantial opportunities to enhance energy efficiency and minimize resource wastage (Garcés et al., 2025). In the context of domestic applications, IoT-based energy monitoring systems function not only as measurement tools but also as mechanisms for control and early warning, assisting users in making more rational and cost-effective consumption decisions (Huang et al., 2023).

The need for such systems has become increasingly urgent in light of electricity subsidy removals in several countries, including Indonesia, which encourage the public to be more conscious of their energy usage. Based on Law No. 30 of 2009 concerning Electricity, the government has implemented adjustments to basic electricity tariffs for households and small industries, directly affecting consumers' operational costs (Poyyamozhi, 2024). This policy shift highlights the importance of adopting IoT-based monitoring systems capable of tracking the consumption of individual household appliances, enabling users to identify sources of energy inefficiency and take targeted conservation measures.

Typically, IoT-based monitoring systems integrate current sensors such as the ACS712 and voltage sensors such as the ZMPT101B to measure electrical parameters with high accuracy (Satya Swaroop, 2025). The data collected are processed using microcontrollers, such as Arduino or NodeMCU, and transmitted via wireless communication modules (e.g., ESP8266) to web-based or mobile application platforms (Jangde & Dwivedi, 2025). This allows users to monitor power, voltage, current, and estimated electricity costs in real time, even from remote locations. Geraldine et al. (2024) demonstrated that systems combining these sensors can achieve current and voltage measurement accuracy with an error margin below 3%, which is sufficient for residential applications (Geraldine et al., 2024).

Beyond monitoring capabilities, the integration of IoT with automated control technologies offers additional benefits. For instance, relay modules can be programmed to disconnect power when consumption exceeds a specified threshold, preventing equipment damage and avoiding unnecessary electricity use (Mendoza et al., 2024). Furthermore, the analysis of historical consumption data can be leveraged to develop predictive models of household energy demand, which are valuable for load planning and microgrid management (Dat et al., 2023).

This concept aligns with the paradigm of smart grids and cyber-physical systems, wherein physical devices, sensors, and computational systems operate in an integrated manner to optimize resource utilization (Garcés et al., 2025). Recent studies suggest that IoT systems enhanced with machine learning algorithms can improve the accuracy of energy consumption forecasting by up to 20% compared to conventional methods (Huang et al., 2023). This underscores the significant potential of IoT-based monitoring

systems to transform household energy consumption behavior toward greater efficiency and sustainability.

Despite numerous prototypes having been developed, a substantial research gap remains: relatively few studies integrate current and voltage measurement, cost calculation, and energy demand prediction into a single, user-friendly platform (Rao, 2024). Therefore, this study aims to design and implement a real-time, accurate IoT-based household energy monitoring system with predictive capabilities. The proposed system is expected not only to provide technical reliability but also to offer a practical solution that can be replicated widely to support sustainable energy-saving efforts.

METHODS

This study employs an experimental research methodology to design, implement, and evaluate an Internet of Things (IoT)-based household electricity monitoring system capable of providing real-time measurement of voltage, current, and power consumption. The design integrates both hardware and software components, emphasizing accuracy, reliability, and ease of data accessibility for end users.

The hardware configuration consists of an Arduino Uno microcontroller serving as the primary processing unit, a NodeMCU ESP8266 module for wireless communication, a ZMPT101B voltage sensor, and an ACS712 current sensor. These sensing modules have been widely utilized in energy monitoring applications due to their accuracy, affordability, and ease of integration (Satya Swaroop, 2025). Additionally, the system incorporates a relay module for load control, a 2x16 Liquid Crystal Display (LCD) for local visualization, and a regulated 12V power supply. Ancillary tools and materials, including a push button, multimeter, jumper wires, and soldering equipment, are employed for assembly, calibration, and testing.

The research process begins with a schematic design phase, in which all component interconnections are mapped to ensure compatibility, minimize electrical noise, and prevent signal interference during data acquisition. This stage follows recommended IoT system design guidelines for energy applications (Rao, 2024). Once the schematic is finalized, the prototype is assembled. This process involves connecting the ZMPT101B sensor to the Arduino Uno's analog pin A0 and the ACS712 sensor to analog pin A1, while the relay, LCD, and NodeMCU are connected to designated digital and communication pins.

Calibration of the voltage and current sensors is conducted to align the Analog-to-Digital Converter (ADC) output values with reference readings obtained from a calibrated digital multimeter, as recommended in previous calibration methodologies (Mendoza et al., 2024). The calibration process ensures that measurement accuracy remains within a ±3% error margin, consistent with recent findings on IoT-based energy monitoring accuracy.

Once deployed, the system continuously measures the voltage ***(V)*** and current ***(I)*** of the connected load. The instantaneous electrical power ***(P)*** is calculated using the formula:

$$P = V \times I \quad \text{..........................(1)}$$

where ***P*** is expressed in watts, ***V*** in volts, and ***I*** in amperes. The total energy consumption ***(E)*** over time is determined by:

$$E = \frac{1}{1000} \int P \, dt \quad \text{.....................(2)}$$

where ***E*** is measured in kilowatt-hours (kWh). The cost of electricity usage is calculated by multiplying ***E*** by the local tariff rate. This dual computation technical and financial provides users with actionable insights into their energy consumption patterns (Dat et al., 2023).

The operational workflow begins when the connected load is activated, prompting the sensors to capture analog signals corresponding to voltage and current. The Arduino Uno processes these signals and sends the results to two destinations: (1) the 2x16 LCD for immediate on-site display, and (2) a cloud server via the NodeMCU ESP8266 module for remote monitoring. The latter enables users to access their consumption data through an online dashboard, aligning with smart home integration principles (Huang et al., 2023).

For validation, a series of controlled experiments are conducted using various household appliances, including a refrigerator, electric iron, single-phase AC motor, laptop charger, soldering iron, water dispenser, television, incandescent lamp, and electric fan. Each appliance operates for a fixed two-hour interval, during which voltage, current, and calculated power values are recorded. The system's accuracy is assessed by comparing its readings with those of a reference instrument, and the percentage error is determined using:

$$\%\,\text{Error} = \frac{|V_{\text{measured}} - V_{\text{reference}}|}{V_{\text{reference}}} \times 100\% \quad \text{....................................(3)}$$

Where V_{measured} is the system output and $V_{\text{reference}}$ is the value obtained from the calibrated multimeter. The same method applies to current measurements.

System performance is evaluated not only in terms of measurement accuracy but also in data synchronization between the local LCD and the remote server. Minimal latency and data consistency are considered key performance indicators. The relay module's functionality is further tested to ensure that it can automatically disconnect loads when consumption exceeds a predefined threshold, supporting energy conservation practices recommended in modern IoT-enabled energy management systems (Poyyamozhi, 2024).

Through this methodological approach, the developed system fulfills both functional and accuracy requirements for residential energy monitoring, offering a practical, scalable, and low-cost solution that aligns with global smart grid and sustainable energy objectives.

RESULTS AND DISCUSSION

The developed Internet of Things (IoT)-based monitoring system successfully provided real-time measurements of voltage, current, instantaneous power, energy consumption (kWh), power factor, and cost estimation. These measurements were accessible both locally, via an LCD interface, and remotely, through a cloud-based server. The evaluation was conducted on nine common household appliances, representing both resistive and inductive load characteristics. Energy consumption was calculated using the standard electrical engineering relation:

$$E = \frac{1}{1000}\int P\,dt \qquad \text{.......................................(4)}$$

Where ***E*** is in kilowatt-hours (kWh), and ***P*** is the instantaneous power in watts. Power factor (PF) was calculated as:

$$PF = \frac{P}{S} \qquad \text{..(5)}$$

Where ***S*** is the apparent power in volt-amperes (VA) (Garcés et al., 2025; Rao, 2024). The system's data acquisition design included filtering to reject invalid readings and timestamp synchronization to minimize bias introduced by grid voltage fluctuations (Huang et al., 2023).

Measurement Accuracy of Voltage and Current

Validation was performed by comparing system readings with a calibrated reference instrument. The results indicated an average voltage error of 0.30% and an average current error of 0.28%, which are well within the accuracy requirements for residential energy monitoring applications. These values are consistent with recent reports on IoT-based smart meters, which suggest that an error margin below 1% is considered high precision for field applications (Garcés et al., 2025).

Table 1. Consolidated Accuracy Table (Voltage, Current, and Apparent Power)

Appliance	V_sensor (V)	V_ref (V)	V_error (%)	I_sensor (mA)	I_ref (mA)	I_error (%)	Apparent Power (VA)
Refrigerator	220	220	0.00	660	662	0.30	145.20
Iron	219	220	0.45	1268	1269	0.07	277.69
AC Motor 1φ	219	219	0.00	501	500	0.19	109.72
Laptop Charger	219	220	0.45	422	420	0.47	92.42
Soldering Iron	219	220	0.45	132	132	0.00	28.91
Water Dispenser	220	220	0.00	158	159	0.63	34.76
Television	220	220	0.00	449	450	0.22	98.78
Incandescent Lamps	215	217	0.90	581	580	0.17	124.92
Fan	218	219	0.45	184	183	0.54	40.11

The low error values suggest that the ADC calibration and voltage-current mapping procedures were effective. Table 1 consolidates the measured and reference values of

voltage and current, along with percentage errors and the calculated apparent power, providing a comprehensive overview of the system's measurement performance.

Energy Consumption Analysis

Energy monitoring over a 120-minute interval revealed significant variation among the tested appliances. The highest consumption was observed in incandescent lamps (≈0.36 kWh), followed by a single-phase AC motor (≈0.19 kWh), iron (≈0.18 kWh), fan (≈0.18 kWh), and television (≈0.17 kWh). The lowest consumption was recorded for the soldering iron (≈0.04 kWh).

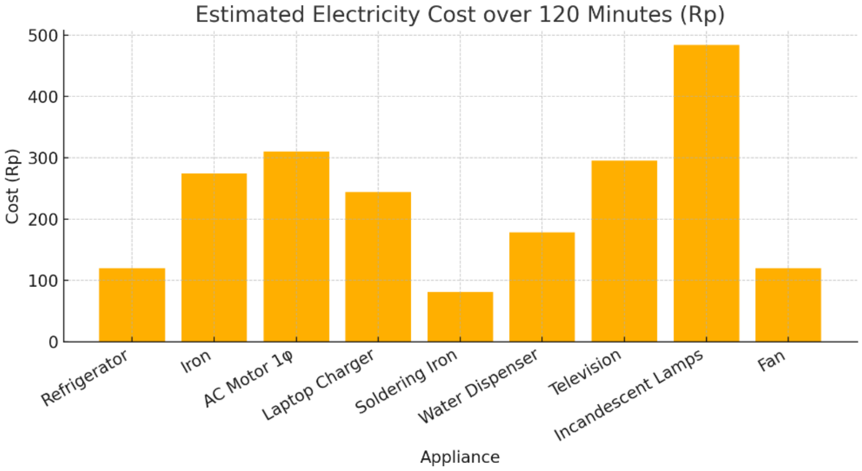

Figure 1. Energy Consumption (kWh) over 120 Minutes

These results align with the known inefficiency of incandescent lamps, where up to 90% of the electrical energy is dissipated as heat rather than converted into light. This low luminous efficacy and short lifespan (~1,000 hours) make them substantially less energy-efficient than modern alternatives such as LEDs (Rao, 2024). Figure 1 illustrates the comparative energy consumption across all appliances.

Cost Estimation

Electricity cost estimation was derived from the measured energy consumption and the applicable tariff per kWh. As expected, the cost profile closely followed the kWh values: incandescent lamps incurred the highest cost over 120 minutes, while the soldering iron incurred the lowest. This observation reinforces the system's practical value in enabling data-driven energy-saving decisions. For example, replacing incandescent lamps with energy-efficient lighting could lead to substantial savings over time (Jangde & Dwivedi, 2025; Mendoza et al., 2024).

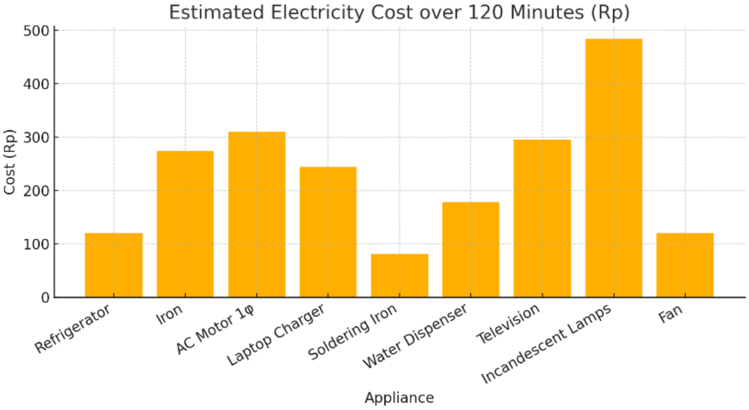

Figure 2. Estimated Electricity Cost over 120 Minutes (Rp)

Furthermore, the system incorporates a relay module, which enables load control based on predefined current or power thresholds. This functionality aligns with demand-side management strategies recommended in contemporary smart energy systems (Bedi et al., 2020; Garcés et al., 2025).

Remote Monitoring Performance

The server-based monitoring, implemented via the Adafruit IO platform, achieved a transmission latency of approximately 10–15 seconds, which is acceptable for quasi-real-time applications in residential IoT systems (Angdresey et al., 2025; Huang et al., 2023). Data consistency between the local LCD display and the remote dashboard was maintained, with only minor discrepancies caused by transient voltage fluctuations.

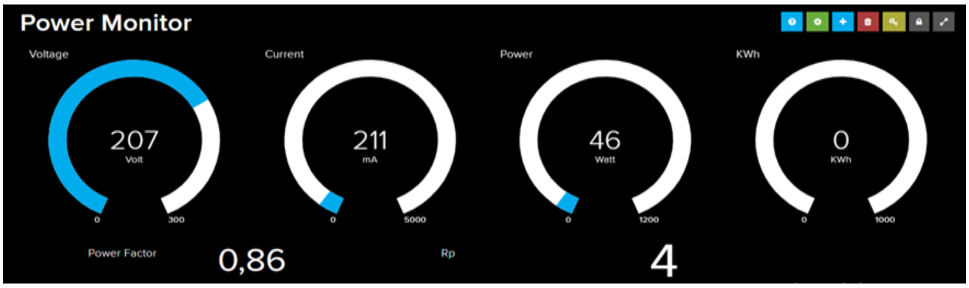

Figure 3. Adafruit IO Platform

The ability to monitor key parameters remotely voltage, current, power, kWh, power factor, and cost provides users with actionable insights without requiring physical access to the monitoring unit (Cascone et al., 2023; Rahman et al., 2025). This feature is particularly valuable for energy management in multi-room households or small businesses.

Technical and Practical Implications

From a technical perspective, the integration of Arduino Uno, NodeMCU ESP8266, ACS712, and ZMPT101B offers a balanced combination of affordability, accuracy, and

replicability. The system's modular architecture also supports potential upgrades, such as integrating power factor correction or harmonics analysis. From a practical standpoint, granular consumption data empower users to target the most energy-intensive appliances for replacement or operational scheduling.

Future enhancements could include machine learning-based energy prediction models, which have been shown to improve forecasting accuracy by up to 20% over conventional methods (Ediga et al., 2024; Wang & Ahn, 2020). Longitudinal testing under varying seasonal and voltage conditions would further validate the system's robustness and adaptability.

CONCLUSION

This study successfully developed and validated an IoT-based household electricity monitoring system integrating Arduino Uno, NodeMCU ESP8266, ZMPT101B voltage sensor, and ACS712 current sensor. The system demonstrated the capability to measure voltage, current, instantaneous power, energy consumption (kWh), power factor, and cost estimation in real time, both locally and remotely. Validation against calibrated reference instruments yielded an average voltage error of 0.30% and an average current error of 0.28%, placing the system within the high-precision category for residential energy monitoring applications.

The monitoring results revealed notable variations in energy consumption across different appliance types, with incandescent lamps recording the highest usage due to their low luminous efficacy, and the soldering iron consuming the least. The system's integrated relay module proved effective for demand-side management by enabling automatic load control based on pre-set thresholds. The cloud-based dashboard, operating with a latency of approximately 10–15 seconds, ensured consistent synchronization with local displays, confirming the system's suitability for real-time or quasi-real-time residential monitoring.

Overall, the proposed system offers a practical, cost-effective, and accurate solution for enhancing household energy management. By providing appliance-level consumption insights, it enables data-driven decision-making that can lead to meaningful energy savings and supports the broader goals of sustainable energy use.

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