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Development and Performance Evaluation of an Energy Monitoring Device with SMS Notification and Automated Billing Features

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ABSTRACT

Manual energy monitoring and billing in multi-unit residential properties remain time-consuming, error-prone, and susceptible to disputes between landlords and tenants. The absence of integrated automation for real-time consumption tracking, billing computation, notification delivery, and power control highlights the need for a unified and cost-effective solution. This study aimed to design, develop, and evaluate an Energy Monitoring Device with SMS notification and automated billing features for small-scale residential applications. A developmental research approach guided by an iterative design model was applied, involving prototype fabrication, functionality testing, and statistical validation of system performance. The device integrates an Arduino MEGA2560 microcontroller, PZEM-004T energy monitoring sensor, SIM800 GSM communication module, ESP8266 Wi-Fi module, solid-state relay (SSR), and a real-time clock module to enable real-time monitoring, automated billing computation, SMS-based notifications, and remote power disconnection. Functionality testing demonstrated 100% operational success across core system features. Efficiency testing showed a mean SMS transmission time of 26.4 seconds, which was significantly lower than the established 32.7-second benchmark. A one-sample t-test confirmed a statistically significant improvement in communication efficiency ($t = -4.52$, $df = 9$, $p < 0.001$). Reliability testing compared device-measured energy readings with conventional submeter measurements, and an F-test indicated no significant variance between the two measurement sets ($F = 1.18$, $p > 0.05$), confirming measurement accuracy and billing consistency. The results demonstrate that the developed prototype provides reliable monitoring performance, improved communication efficiency, and practical applicability for residential energy management, offering landlords a scalable and automated alternative to manual billing systems.

1   INTRODUCTION
1.1   Background of the Problem

Electricity costs have continued to increase in the Philippines, placing financial pressure on households and small-scale property owners. The residential sector remains one of the largest electricity-consuming sectors in the country. According to the Philippine Department of Energy, residential electricity consumption reached approximately 118,000 GWh in 2023,

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highlighting the importance of effective energy monitoring and management within household and rental environments (Department of Energy, 2024).

High electricity tariffs in the Philippines have been associated with structural market conditions, fuel dependency, and regulatory factors, which contribute to affordability concerns among consumers and increased sensitivity to billing accuracy in rental arrangements (Ali et al., 2022). In multi-unit residential properties, landlords are therefore under increasing pressure to provide transparent, accurate, and timely billing systems.

Manual energy monitoring and billing remain common practices in many small rental properties. These methods typically involve periodic meter reading, manual recording of consumption values, handwritten billing computation, and physical bill distribution. Such procedures are time-consuming and susceptible to human error, which can lead to disputes between landlords and tenants when billing discrepancies occur. Similar concerns have been reported in energy management studies, where limited monitoring transparency and delayed consumption reporting contributed to payment delays and operational inefficiencies (Otchere-Appiah et al., 2021). In rental housing environments, these inefficiencies may weaken trust between property owners and tenants and create challenges in revenue collection.

To address these challenges, landlords often adopt submetering systems, prepaid meters, or smart meters. Submetering allows individual monitoring of tenant consumption; however, accuracy limitations and calibration inconsistencies have been reported in some conventional setups, which may affect billing fairness (Koukouvinos et al., 2025). Smart meters provide real-time monitoring and detailed consumption data, which can improve transparency and energy management; however, high installation costs, infrastructure requirements, and limited user acceptance have restricted their widespread adoption in small-scale residential properties (Kochański et al., 2020). Prepaid metering systems shift payment responsibility to advance credit purchase, reducing collection risks, yet they often lack integrated billing notification and remote management capabilities (Qazi et al., 2020).

These limitations highlight the need for an integrated, cost-effective solution capable of combining real-time monitoring, automated billing computation, SMS-based communication, and remote disconnection control within a single device architecture. Such a system could reduce manual workload, improve billing transparency, and enhance operational efficiency for landlords managing multi-unit residential properties.

1.2   Research Gap

Existing energy management systems in residential rental settings remain fragmented in design and function. While smart metering technologies provide real-time monitoring capabilities, they often focus primarily on consumption tracking without integrating automated billing computation or tenant notification mechanisms (Kochański et al., 2020). Similarly, prepaid metering systems address payment enforcement but typically operate as stand-alone financial control tools, lacking continuous monitoring dashboards and flexible billing adjustments (Qazi et al., 2020).

Research on SMS-based energy systems has demonstrated that GSM communication can effectively transmit consumption updates and control commands; however, these implementations are frequently limited to notification or prepaid credit management functions rather than being embedded within a comprehensive billing and control framework (Otchere-Appiah et al., 2021). Moreover, automated power disconnection mechanisms are often available in high-end smart grid infrastructures, yet such solutions require substantial capital investment and advanced infrastructure support, which may not be feasible for small-scale landlords managing low- to mid-income rental properties (Ali et al., 2022).

The literature therefore indicates a persistent integration gap. Existing systems tend to offer isolated features—real-time monitoring, automated billing, SMS communication, or remote control—but rarely combine all four into a unified, low-cost device appropriate for decentralized residential settings. Particularly in small multi-unit properties, landlords require a scalable and economically accessible solution that integrates real-time energy monitoring, automated billing computation, SMS-based notification, and automatic power disconnection within a single system architecture. The absence of such an integrated framework constitutes the primary research gap addressed in this study.

1.3   Objectives of the Study

The primary objective of this study was to develop and evaluate an integrated Energy Monitoring Device with SMS Notification and automated billing features intended for multi-unit residential applications. Specifically, the study aimed to:

- Design and develop an integrated energy monitoring system capable of real-time consumption tracking, automated billing computation, SMS-based communication, and remote power control.

- Construct and assemble a functional prototype using modular hardware and microcontroller-based architecture.

- Test the operational functionality of the system components, including monitoring accuracy, SMS command processing, billing automation, and disconnection mechanisms.

- Evaluate the efficiency and reliability of the device through statistical validation of performance metrics and measurement accuracy.

- Develop a comprehensive user manual to guide installation, operation, configuration, and maintenance of the prototype system.

2   RELATED WORKS

2.1   Energy Monitoring Systems

Energy monitoring systems have evolved toward real-time data acquisition and IoT-enabled architectures to improve transparency, efficiency, and decision-making in residential and commercial energy use. Real-time monitoring allows continuous measurement of voltage, current, power, and cumulative energy consumption, enabling users to detect anomalies, reduce wastage, and optimize load management (Alahakoon & Yu, 2016; Siano, 2014). Recent IoT-based solutions integrate microcontrollers, wireless communication modules, and cloud platforms to transmit consumption data to dashboards or mobile applications, thereby enhancing accessibility and remote supervision (Zanella et al., 2014). Despite these advances, conventional submetering systems used in multi-unit residential settings remain limited in functionality. While they enable separate measurement of tenant consumption, traditional submeters often lack automated billing integration, remote notification features, and dynamic control mechanisms. Calibration inconsistencies, delayed readings, and manual data handling may further affect billing accuracy and transparency (Darby, 2018). These limitations highlight the need for integrated monitoring systems that combine real-time measurement with communication and automated control capabilities within a unified architecture.

2.2   SMS-Based Energy Control Systems

SMS-based energy control systems have been implemented as low-cost communication solutions for remote monitoring and control in distributed energy applications. GSM modules enable two-way communication between users and energy devices, allowing consumption updates, rate adjustments, and control commands to be transmitted without reliance on continuous internet connectivity. Prior implementations reported an average SMS transmission benchmark of 32.7 seconds in prepaid energy monitoring applications, establishing a baseline for evaluating communication efficiency under GSM networks (Amhenrior, 2018). Reliability assessments in similar systems have demonstrated high command success rates when standardized SMS formatting and keyword validation protocols were applied, with performance stability influenced by signal strength and network latency conditions (Alheraish, 2014). Although SMS-based systems provide dependable notification and control capabilities, many existing designs focus primarily on prepaid functionality or isolated command execution rather than integrating automated billing computation and multi-feature system control. These findings underscore the technical feasibility of GSM-based communication while highlighting the need for broader system integration and performance validation in energy management devices.

2.3   Automated Billing in Property Management

Automated billing systems have become central to modern property management, particularly in multi-unit rental environments where accuracy, timeliness, and transparency are critical. Digital rent collection platforms streamline payment processing by reducing manual computation, minimizing clerical errors, and generating automated invoices and payment confirmations (Fields & Rogers, 2021). These systems enhance operational efficiency and improve cash flow stability by enabling scheduled billing cycles, automated reminders, and electronic record keeping. Real-time financial tracking further supports property managers by providing instant access to payment status, outstanding balances, and billing history, which facilitates informed decision-making and reduces administrative workload (Fang et al., 2022). Although many digital property management platforms provide online dashboards and financial analytics, integration with real-time energy consumption monitoring and automated service control remains limited in small-scale residential contexts. This limitation highlights the need for a unified system that combines automated billing with consumption-based monitoring and communication features within a single device architecture.

2.4   Comparative Prior Art Table

Several studies in table 1 have explored different approaches to energy monitoring and billing automation, including IoT-based smart meters, GSM-enabled monitoring systems, and submetering devices. IoT-based energy monitoring platforms allow real-time data acquisition and remote access to electricity consumption information, which improves

transparency and monitoring capability in residential and commercial environments (Alam et al., 2020). GSM-based monitoring systems have also been widely used to transmit energy consumption data and billing information through SMS communication, particularly in areas where internet connectivity may be unstable (Shinde & Kulkarni, 2019). However, many existing systems focus only on monitoring functions without integrating automated billing computation or enforcement mechanisms. Studies on smart energy metering have reported that several monitoring systems lack automated disconnection features, which limits their effectiveness in rental environments where payment compliance must be enforced (Gungor et al., 2018). Furthermore, conventional submetering systems typically require manual billing computation and tenant notification, which introduces operational inefficiencies and increases the likelihood of billing disputes (Kabalci, 2016). These documented limitations highlight the need for an integrated solution capable of combining real-time monitoring, automated billing calculation, SMS-based notification, and remote power control within a unified system architecture.

Table 1. Summarizes selected prior systems relevant to energy monitoring and tenant-based billing applications.

System	Core Components	Key Features	Limitation
IoT-Based Water and Power Monitoring System	ESP8266 module, water meter, power outlet interface, IoT dashboard	Real-time monitoring of electricity and water consumption; remote access via internet	Focused on monitoring only; lacks automated billing computation and SMS-based enforcement
Individualized Electric Consumption Monitoring System for Sub-Metered Tenants	Arduino Mega/Nano, PZEM-004T sensor, relay module, RTC module, OLED display, SD card, GSM/SMS integration	Separate tenant energy tracking; SMS communication; Android application integration	Limited integration of automated billing and power disconnection; higher component complexity
SMS-Based Prepaid Energy Meter	Microcontroller, GSM module (SIM800), relay switching mechanism	SMS credit updates; prepaid billing model; remote cutoff control	Primarily prepaid-based; no real-time dashboard or flexible postpaid billing integration
Conventional Submetering System	Analog/digital submeters, circuit breakers	Individual tenant energy measurement	Manual reading; no automated billing; no remote communication or control

2.5   Study Contribution

This study contributes to the field of residential energy management by proposing an integrated device architecture that consolidates multiple operational functions within a single system. Unlike existing solutions that emphasize either monitoring, prepaid enforcement, or isolated SMS communication, the developed system integrates SMS-based command processing, automated billing computation, automatic power cutoff control, and a WiFi-enabled dashboard for real-time monitoring. This unified configuration enables landlords to manage consumption tracking, billing notification, and service enforcement through coordinated hardware and software modules rather than through separate platforms.

The device was designed as a low-cost, modular prototype using commercially available microcontroller components and energy sensing modules. The modular structure allows flexible scaling, simplified maintenance, and potential future upgrades without requiring full system replacement. By relying on GSM communication and standard WiFi connectivity, the system reduces dependency on complex smart grid infrastructure while maintaining essential automation capabilities.

The system was specifically designed to address operational conditions in Philippine residential rental settings, where small-scale landlords commonly rely on manual billing practices and limited technical infrastructure. The proposed solution therefore emphasizes affordability, ease of installation, and functional reliability within decentralized, multi-unit residential environments.

3   METHODOLOGY
3.1   Research Design

This study employed a developmental research design focused on the systematic creation, refinement, and evaluation of a functional energy monitoring prototype. An iterative design model guided the process, allowing continuous improvement through cycles of planning, assembly, testing, and modification until performance objectives were achieved. The research involved prototype fabrication using modular hardware components, microcontroller-based control logic, and integrated communication modules. Following construction, the system underwent structured functional testing to verify operational features such as monitoring accuracy, SMS command processing, automated billing, and power disconnection mechanisms. Reliability testing was subsequently conducted to assess measurement consistency and system stability under repeated operation, ensuring that the device performed accurately and dependably within the intended residential application context.

This developmental study followed a sequential procedure consisting of system design, hardware assembly, wiring integration, sensor calibration, functionality testing, efficiency testing, and reliability testing under controlled load conditions.

3.2   System Architecture

Figure 1 illustrates the overall system architecture of the developed Energy Monitoring Device. The process begins with the energy input from the AC load of each residential unit, which is measured by the PZEM-004T energy sensing module coupled with a current transformer. The measured electrical parameters are transmitted to the Arduino MEGA2560 controller, which serves as the central processing unit of the system. The controller processes real-time consumption data, computes billing values, and manages system logic using the integrated real-time clock module.

From the controller, two major functional pathways are established. The first pathway enables communication through the SIM800 GSM module for SMS-based notifications and command processing, as well as the ESP8266 Wi-Fi module for dashboard-based monitoring. The second pathway controls system outputs, including the solid-state relay for automatic power disconnection, LCD display for on-site monitoring, and automated billing and alert generation. This architecture demonstrates the integration of sensing, processing, communication, and control components within a unified device framework.
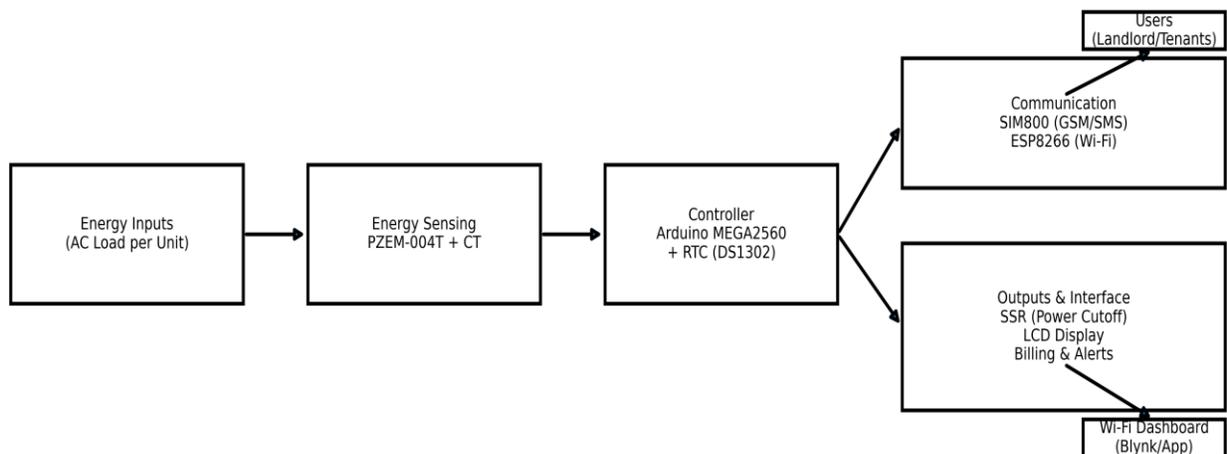

Figure 1. System Block Diagram of the Energy Monitoring Device

Figure 2 presents the Input–Process–Output (IPO) framework of the energy monitoring system. The input stage consists of electrical parameters from the AC load, configured energy rates, and authorized SMS commands from the user. These inputs are processed by the controller through real-time monitoring, automated billing computation, command validation, and programmed cutoff logic. The processing stage transforms raw electrical data into computed billing information and system decisions. The output stage then generates billing details, transmits SMS notifications, updates the Wi-Fi dashboard, and activates automatic power disconnection when required. This IPO structure demonstrates how the system integrates measurement, computation, communication, and control within a unified operational flow.
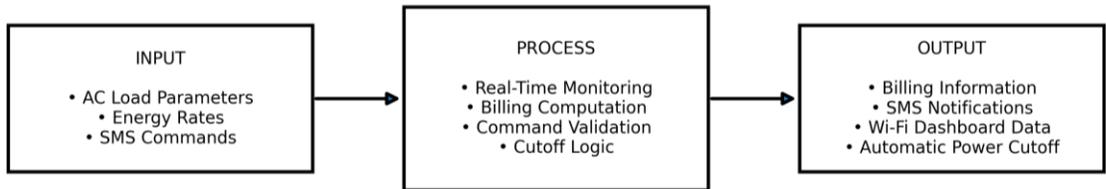
Figure 2. Input-Process-Output (IPO) Framework of the Energy Monitoring System

3.2.1 Component Integration

The system components in figure 3 were integrated through a centralized microcontroller-based architecture in which the Arduino MEGA2560 functioned as the core processing unit. The PZEM-004T energy sensing module was interfaced with the controller through serial communication to transmit real-time voltage, current, power, and energy data. The SIM800 GSM module was connected via serial pins to enable SMS-based command reception and notification transmission, while the ESP8266 Wi-Fi module provided wireless data communication to the monitoring dashboard. The solid-state relay (SSR) was connected to the controller's digital output pins to allow controlled power disconnection based on programmed billing logic. The real-time clock module was integrated to ensure accurate billing cycle tracking and deadline monitoring. All components were synchronized through programmed control logic, ensuring coordinated data acquisition, processing, communication, and output control within a single cohesive system architecture.
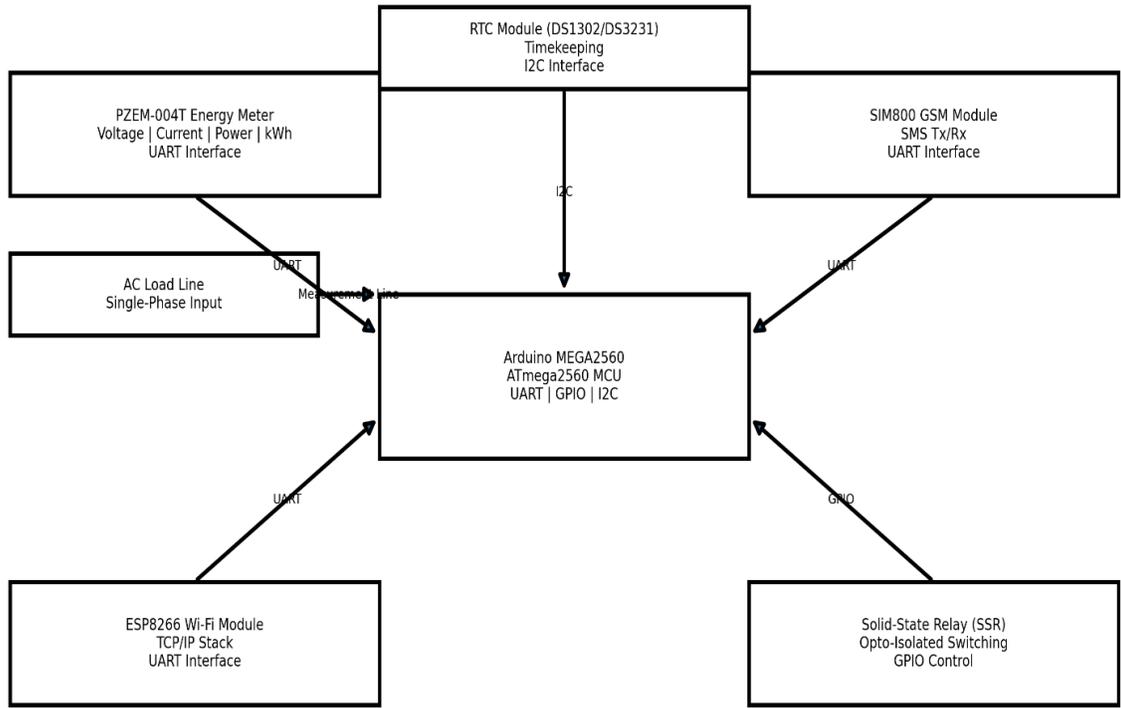

Figure 3. System Components

The Arduino MEGA2560 served as the main controller due to its multiple serial communication ports and sufficient digital I/O capacity. The PZEM-004T energy sensor was interfaced through serial communication for real-time acquisition of voltage, current, power, and cumulative energy readings. The SIM800 GSM module was connected through UART for SMS transmission and reception, while the ESP8266 Wi-Fi module was used to upload monitoring data to the Blynk dashboard platform. The RTC module provided date and time reference for billing and cutoff scheduling, and the SSR was used as the switching device for automatic load disconnection.

3.2.2 Hardware Components

Figure 4 shows that the system was constructed using modular hardware components selected for compatibility, reliability, and cost efficiency. The Arduino MEGA2560 served as the central microcontroller, providing sufficient input/output pins and memory capacity to manage multiple communication modules and control functions simultaneously. The PZEM-004T energy sensor was used to measure voltage, current, power, and cumulative energy consumption in real time, enabling accurate billing computation. The SIM800 GSM module facilitated SMS-based communication, allowing remote command processing and automatic transmission of billing notifications. The ESP8266 Wi-Fi module enabled wireless data transmission to an online dashboard for real-time monitoring and system oversight. A solid-state relay (SSR) was integrated to execute automatic power disconnection when billing conditions were not met, ensuring safe and reliable switching without mechanical wear. The real-time clock (RTC) module maintained accurate date and time tracking, which was essential for billing cycle management, due date monitoring, and automated cutoff scheduling. Together, these components formed an integrated hardware framework supporting sensing, processing, communication, and control functions.

The Arduino MEGA2560, based on the ATmega2560 microcontroller, operated at 5 V and provided sufficient I/O pins and memory for multi-module integration. The PZEM-004T module was used for AC parameter measurement within the residential testing range. The SIM800 GSM module enabled SMS-based command reception and notification transmission over a 2G network. The ESP8266 module provided wireless connectivity to the dashboard through Wi-Fi. The SSR served as the electronically controlled switching device for load disconnection, while the RTC module maintained accurate timekeeping for billing due dates and cutoff scheduling. A regulated 12 V, 5 A power supply was used to energize the control circuit and communication modules.
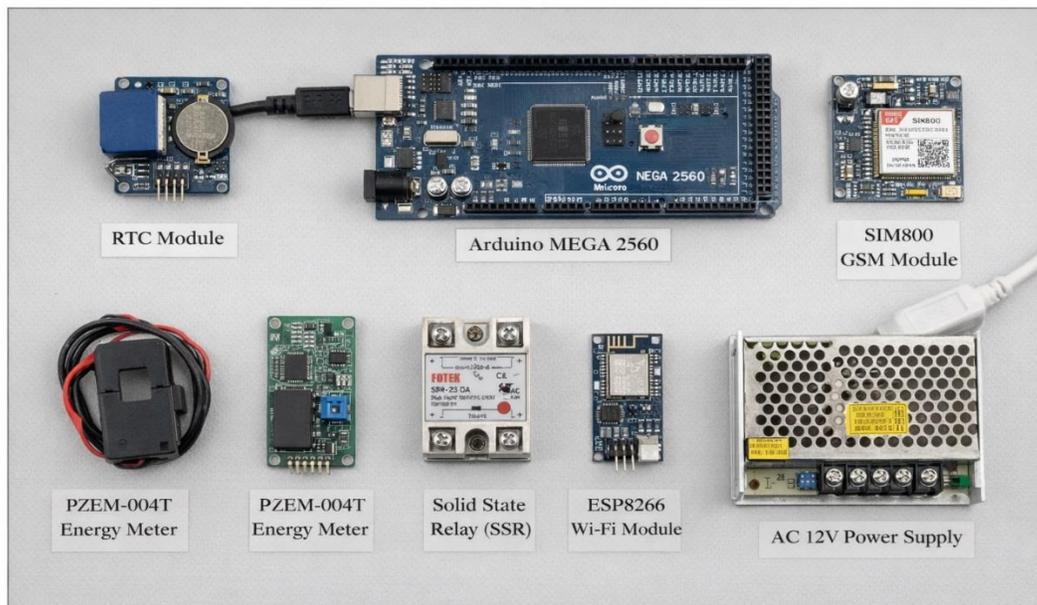

Figure 4. Hardware Components

3.2.3   Software Logic

The software logic was programmed within the Arduino MEGA2560 to coordinate monitoring, communication, billing, and control functions in a structured sequence. SMS command parsing was implemented to detect and validate predefined keywords received through the SIM800 GSM module. Incoming messages were filtered, formatted, and interpreted to execute authorized actions such as rate modification or system reset.

Billing computation was performed using real-time energy consumption data obtained from the PZEM-004T module. The system continuously accumulated kilowatt-hour readings and multiplied the total consumption by the configured energy rate to generate updated billing amounts. Energy rate update functionality allowed authorized users to modify tariff values through structured SMS commands, which were then stored and applied immediately in subsequent billing calculations.

Due date monitoring was managed through the integrated real-time clock module, enabling the system to compare the current date against predefined billing deadlines. Automated disconnection logic was triggered when unpaid balances exceeded the due date, prompting the controller to activate the solid-state relay and interrupt power supply. This programmed sequence ensured synchronized communication, billing accuracy, and controlled service enforcement within the device architecture.
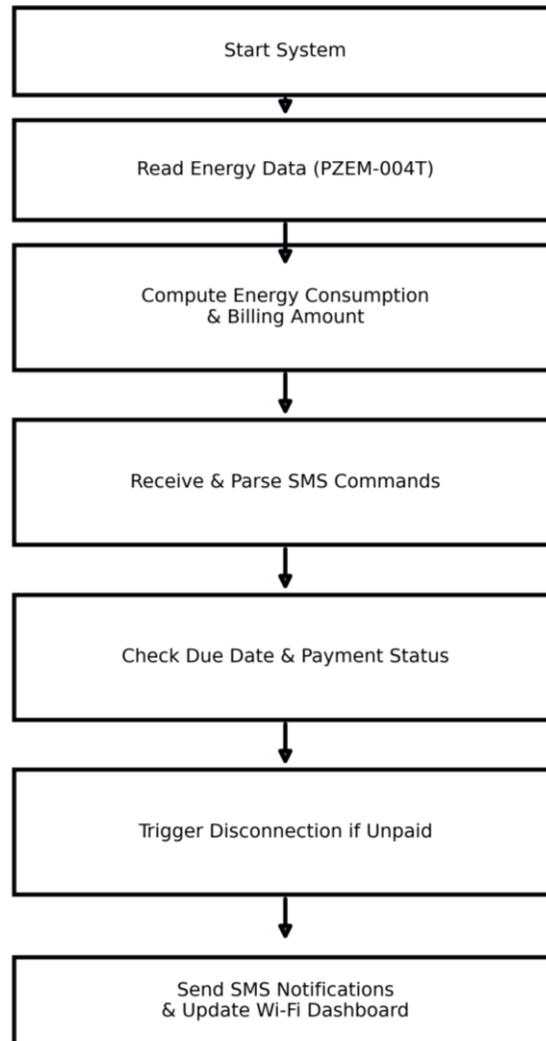

Figure 5. Simplified System Flowchart of the Energy Monitoring Device

Figure 5 presents the operational sequence of the system from initialization to output execution. The process begins with system startup and real-time acquisition of electrical data from the energy sensing module. The controller then computes total energy consumption and corresponding billing amounts based on predefined tariff rates. Incoming SMS commands are received and parsed to allow authorized configuration updates. The system continuously checks billing deadlines and payment status using the real-time clock module. If unpaid balances exceed the due date, automated disconnection logic is triggered through the solid-state relay. Finally, SMS notifications are transmitted and the Wi-Fi dashboard is updated to reflect current billing and system status. The flowchart illustrates the structured decision-making and control logic embedded within the device architecture.

Energy data were sampled at fixed intervals of 1 second to allow continuous updating of monitoring and billing values. SMS commands were parsed using predefined keywords for rate update, due date modification, cutoff date update, and payment status control. Updated billing parameters were stored in the controller logic and immediately applied to subsequent computations. Monitoring data were transmitted to the Blynk dashboard through the ESP8266 Wi-Fi module for

real-time visualization. Automatic cutoff was triggered when the stored payment status remained unpaid beyond the programmed cutoff date.

3.3   Prototype Development

The prototype in figure 6 was developed through systematic assembly of hardware components within a structured enclosure designed for residential application. All modules were mounted securely on a non-conductive base to ensure mechanical stability and organized internal layout. The Arduino MEGA2560 served as the central unit, with peripheral components positioned to minimize signal interference and wiring congestion.

Wiring configuration followed standardized electrical practices. The PZEM-004T energy sensor was connected in series with the load line to accurately measure voltage, current, and power parameters. Serial communication lines were established between the controller and both the SIM800 GSM module and ESP8266 Wi-Fi module. Digital output pins were allocated for relay control, while separate regulated lines were used for logic-level communication to prevent voltage mismatch.

Power supply integration was implemented using a regulated DC power module to convert AC mains input into stable voltage levels required by the microcontroller and communication modules. Voltage regulators ensured consistent operation and prevented fluctuations that could affect data accuracy or system stability.
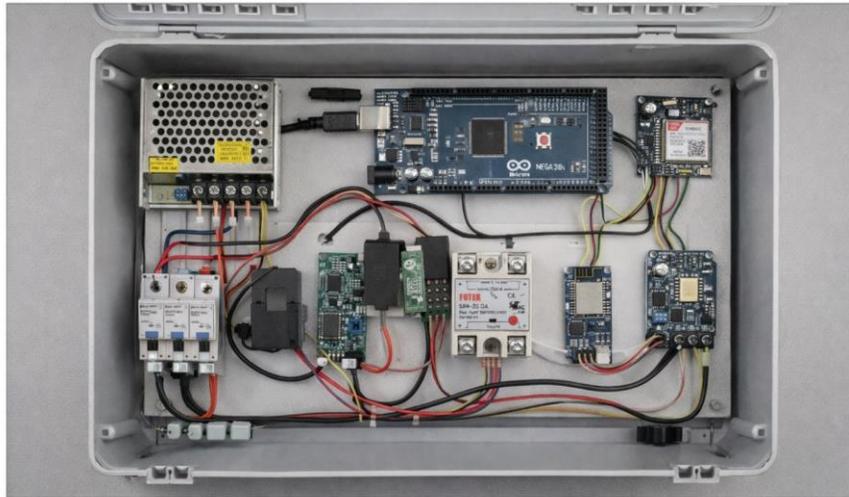

Figure 6. Prototype within Enclosure

The communication modules were configured to operate independently yet synchronously with the controller. The SIM800 module was interfaced for SMS transmission and reception, while the ESP8266 enabled wireless connectivity to the monitoring dashboard. Both modules were tested for signal stability and command responsiveness during integration.

Safety protections were incorporated to ensure operational reliability. Circuit breakers were installed to prevent overcurrent conditions, and proper insulation was applied to high-voltage lines. The solid-state relay provided electrical isolation between control and load circuits, reducing mechanical wear and enhancing switching safety. These protective measures ensured that the prototype complied with fundamental electrical safety standards for residential deployment.

A. Assembly The internal layout was arranged by functional grouping, with sensing, control, communication, and switching components placed in separate positions to reduce wiring congestion and possible signal interference.

B. Wiring Configuration: The PZEM-004T module was wired to the AC line for voltage sensing and to the current transformer for load current measurement. The SIM800 GSM module and ESP8266 Wi-Fi module were connected to dedicated serial communication lines of the Arduino MEGA2560. The SSR was connected to a digital output pin for switching control, while the RTC module was linked to the controller for continuous date and time reference. Separate regulated supply lines were used for low-voltage modules to avoid instability due to voltage fluctuation.

C. Censor Calibration: Prior to formal testing, the PZEM-004T sensor was calibrated by comparing its readings with those obtained from a reference submeter under known load conditions. Voltage, current, and energy readings were

observed across repeated trials, and the sensor output was verified for consistency before use in functionality and reliability testing.

D. Load Types and Ranges Used During Testing: Testing was conducted using representative residential loads such as lighting devices, fan loads, charger-based loads, and other low- to moderate-power household appliances. The test load range was selected to reflect common residential electricity consumption conditions applicable to small rental units.

E. GSM Network Conditions: The SIM800 module operated under available local GSM network conditions during testing. SMS performance was evaluated under standard signal availability in the test area, and transmission time was measured from command sending to successful message receipt.

F. Wi-Fi Dashboard Platform: The Wi-Fi dashboard platform used in the study was Blynk, which enabled real-time visualization of monitored energy values, billing status, and selected device parameters through wireless data transmission from the ESP8266 module.

3.4   Testing Procedures

Testing procedures were conducted to evaluate the operational performance, efficiency, and reliability of the developed energy monitoring device. All tests were performed in a controlled residential electrical environment to simulate typical household conditions. The prototype system was connected to representative residential electrical loads while operating under standard AC mains supply. Each functional test was conducted through ten repeated trials to verify consistency and reliability of system responses. The acceptance criterion for functionality tests was defined as successful execution of the programmed operation without system error or malfunction across all trials.

3.4.1   Functionality Tests

Functionality testing was conducted to verify that all major operational features of the system performed according to the programmed control logic. Each feature was evaluated through ten independent trials to ensure consistent execution. The SMS update function was tested by sending predefined command messages to the SIM800 GSM module and verifying successful reception, parsing, and execution by the controller. Successful system response in all trials was considered the acceptance criterion. The energy rate modification feature was evaluated by transmitting authorized SMS commands to update the configured energy tariff. The acceptance criterion required that the updated rate be correctly applied in subsequent billing calculations without computational error.

The due date modification function was tested by sending commands that updated billing deadlines. The system's RTC module was then monitored to verify that the controller correctly referenced the new due date in its internal billing logic. The cutoff control logic was tested by simulating overdue billing conditions. The system was expected to activate the solid-state relay to disconnect the electrical load once the programmed due date had passed without payment confirmation. Correct relay activation constituted successful execution. The bill generation and delivery functions were tested by comparing automatically generated billing values with manually computed totals derived from recorded kilowatt-hour consumption. Accurate SMS transmission of billing information and correct dashboard updates served as the acceptance criteria.

3.4.2   Efficiency Testing

Efficiency testing was conducted to measure the communication performance of the SMS notification system. The time required for SMS transmission was measured as the interval between the moment a command was sent to the device and the moment the corresponding notification message was successfully received by the user. A total of ten trials were conducted under the available GSM network conditions in the test location. The recorded transmission times were averaged to determine the mean SMS transmission time of the developed system. The obtained mean transmission time was compared with a 32.7-second benchmark value reported in previous SMS-based energy monitoring research. This benchmark served as the reference value representing the typical response time of earlier GSM-based monitoring implementations. A one-sample t-test was applied to determine whether the observed mean SMS transmission time of the developed system was significantly different from the 32.7-second benchmark. The null hypothesis assumed no difference between the observed mean and the benchmark value. Statistical significance was evaluated at a 0.05 significance level.

3.4.3   Reliability Testing

Reliability testing was performed to evaluate the measurement consistency of the developed system and the accuracy of the automated billing computation. The first reliability assessment involved comparing energy readings obtained from the PZEM-004T energy monitoring module with readings recorded from a calibrated reference submeter under identical load conditions. Measurements were recorded across ten repeated trials to evaluate variance consistency. The second reliability assessment compared automated billing outputs generated by the system with manually computed billing values based on the same energy consumption readings and tariff rates.

An F-test (variance ratio test) was applied to determine whether a statistically significant difference existed between the variance of device-generated measurements and reference measurements. If the computed F value did not exceed the critical value at the 0.05 significance level, the device measurements were considered statistically consistent with the reference measurements, indicating acceptable reliability.

3.5   Statistical Analysis

Table 2 summarizes the statistical methods used to evaluate the performance of the developed system. The mean percentage was applied as a descriptive measure to determine the success rate of functionality tests and overall operational efficiency. A one-sample t-test was conducted to compare the observed SMS transmission time against the established 32.7-second benchmark to assess communication efficiency. An F-test was used to compare the variance of device-based energy readings with submeter measurements and automated billing computations with manual calculations to determine reliability. All inferential analyses were evaluated at a 0.05 level of significance to establish statistical validity of the system's efficiency and consistency.

The functionality datasets were summarized using mean percentage, the SMS transmission dataset was analyzed using a one-sample t-test against the 32.7-second benchmark, and the variance of energy and billing measurements was evaluated using the F-test at a 0.05 level of significance.

Table 2. Summary of Statistical Analysis Methods

Statistical Tool	Purpose	Formula / Basis	Decision Rule
Mean Percentage	To summarize functionality success rate and SMS efficiency performance	Mean = (Sum of Observations / n) × 100%	Descriptive evaluation only
One-Sample t-Test	To compare observed SMS transmission time with 32.7-second benchmark	$t = (\bar{x} - \mu) / (s / \sqrt{n})$	Reject H_0 if $p < 0.05$
F-Test (Variance Ratio)	To compare variance of device readings vs submeter and automated billing vs manual computation	$F = s_1^2 / s_2^2$	Reject H_0 if $p < 0.05$

4   RESULTS AND DISCUSSION
4.1   Device Functionality

Functionality testing confirmed that all programmed features of the developed energy monitoring device operated correctly. SMS command reception, energy rate modification, automated bill generation, and power cutoff activation were executed successfully across all trials. Each operational function achieved a 100% success rate, indicating that the integrated sensing, communication, billing, and control modules performed consistently within the implemented system architecture.

4.2   SMS Efficiency Analysis

The efficiency of the communication system was evaluated by comparing the observed SMS transmission time with the previously reported 32.7-second benchmark for GSM-based monitoring systems. Ten transmission trials were conducted under normal GSM network conditions.

The observed mean transmission time was 26.4 seconds, with a standard deviation of 4.41 seconds and sample size of 10. A one-sample t-test was conducted to determine whether the observed mean differed significantly from the benchmark value. The computed statistical results were:

- Observed mean = 26.4 s

- Benchmark mean = 32.7 s

- Standard deviation = 4.41 s

- Sample size = 10

- Test statistic t = –4.52

- Degrees of freedom df = 9

- $p < 0.001$

- 95% Confidence Interval = 23.25 s to 29.55 s

Since the p-value is lower than the 0.05 significance level, the null hypothesis was rejected. The results indicate that the developed system achieved a statistically significant reduction in SMS transmission time compared with the benchmark reference. This demonstrates improved communication responsiveness and confirms the suitability of the GSM-based notification system for real-time billing alerts and remote command execution.

4.3   Energy Monitoring Reliability

Reliability testing evaluated the consistency of device-generated measurements compared with readings obtained from a calibrated reference submeter. An F-test was used to compare the variance of the two measurement datasets. Statistical outputs were as follows:

- Device measurement variance = 5.20

- Submeter variance = 4.40

- F statistic = 1.18

- Degrees of freedom $df_1 = 9$, $df_2 = 9$

- $p > 0.05$

Because the computed F value did not exceed the critical value at the 0.05 significance level, the null hypothesis was not rejected. This indicates that no statistically significant difference exists between the measurement variances, confirming that the device readings are consistent with the reference submeter measurements.

A similar variance comparison was performed between automated billing outputs and manually computed billing values:

- Automated billing variance = 3.10

- Manual billing variance = 2.90

- F = 1.07

- $df_1 = 9$, $df_2 = 9$

- $p > 0.05$

These results demonstrate that the automated billing computation produced outputs statistically equivalent to manual calculations, confirming the reliability of the billing algorithm.

4.4   System Performance Summary Table

Table 3 presents the SMS transmission times recorded during the communication efficiency testing of the developed energy monitoring device. The table lists the individual transmission durations observed across ten trials, measured from the moment an SMS command was initiated to the successful receipt of the corresponding system notification. The

recorded values show relatively consistent transmission times under the available GSM network conditions. The computed mean transmission time of 26.4 seconds and standard deviation of 4.41 seconds indicate stable communication performance with moderate variability across trials. These results demonstrate that the SMS-based communication mechanism of the system operates within a predictable response interval. The mean value obtained from these trials served as the basis for the subsequent one-sample t-test used to evaluate whether the system achieved a statistically significant improvement compared with the previously reported 32.7-second benchmark for SMS-based energy monitoring implementations. Variance comparison results:

- Device measurement variance = **5.20**

- Submeter variance = **4.40**

Table 3. SMS Transmission Time Trials

Trial	SMS Transmission Time (seconds)
1	19
2	23
3	24
4	25
5	26
6	27
7	28
8	29
9	30
10	33
Mean	**26.4**
Standard Deviation	**4.41**
Sample Size (n)	**10**

Table 4 presents the comparison between the energy readings obtained from the developed monitoring device and those recorded from the reference submeter during the reliability testing trials. Each trial shows closely corresponding kilowatt-hour measurements between the two instruments, indicating consistent monitoring performance under the same electrical load conditions. The small differences observed between the device readings and the reference measurements remain within acceptable measurement tolerance for residential energy monitoring applications. This comparison demonstrates that the PZEM-004T sensor integrated into the system can provide energy consumption measurements that are comparable to those obtained from a conventional calibrated submeter. The data presented in the table therefore support the statistical reliability analysis conducted through the F-test, confirming that the developed monitoring device produces stable and consistent energy measurement results suitable for automated billing computation.

Table 4. Energy Monitoring Reliability Comparison

Trial	Device Energy Reading (kWh)	Reference Submeter (kWh)
1	0.82	0.80
2	1.14	1.11
3	0.95	0.93
4	1.23	1.20
5	0.78	0.76
6	1.10	1.07
7	0.89	0.87
8	1.05	1.02
9	0.92	0.90

Trial	Device Energy Reading (kWh)	Reference Submeter (kWh)
10	1.18	1.15

Table 5 summarizes the overall performance of the developed energy monitoring device across its major operational functions. The results show that the system achieved a 100% success rate in executing SMS update commands and energy rate modifications, confirming the reliability of the communication and configuration features. The automated billing function generated values consistent with manual calculations, indicating accurate computation of electricity charges based on measured energy consumption. The power cutoff mechanism operated as programmed, demonstrating that the system can enforce billing compliance through automatic load disconnection when payment deadlines are exceeded. In terms of communication efficiency, the observed mean SMS transmission time of 26.4 seconds was significantly lower than the 32.7-second benchmark, indicating improved responsiveness of the GSM-based notification system. Reliability testing further confirmed that the device's energy readings and automated billing computations showed no significant variance compared with reference measurements, as indicated by the F-test results. These findings collectively demonstrate that the system performed reliably in monitoring, communication, billing computation, and control functions within the tested residential energy management environment.

Table 5. System Performance Summary

Performance Category	Evaluation Metric	Result	Interpretation
SMS Update Function	Command execution success rate	100%	Commands executed successfully
Energy Rate Modification	Accuracy of tariff update	100% accurate	Updated rates applied correctly
Bill Generation	Comparison with manual calculation	No deviation	Accurate billing computation
Power Cutoff Logic	Response to overdue balance	Functional	Relay activated as programmed
SMS Transmission Efficiency	Mean time vs 32.7 s benchmark	26.4 s mean	Significantly faster communication
Energy Reading Reliability	Variance comparison (F-test)	$F = 1.18$, $p > 0.05$	Comparable to reference submeter
Billing Reliability	Variance comparison (F-test)	$F = 1.07$, $p > 0.05$	Automated billing consistent

4.5   Discussion

The findings align with prior SMS-based energy monitoring studies, which demonstrated the feasibility of GSM communication for remote command execution and notification delivery, but often lacked integrated billing automation and multi-feature control frameworks. The significant improvement in SMS transmission efficiency and the absence of variance in reliability testing indicate that the developed system extends previous implementations by combining communication efficiency with validated measurement accuracy. The integration of Wi-Fi dashboard monitoring reflects advances in IoT-based energy systems, where real-time data access enhances transparency and user control. Unlike conventional IoT monitoring platforms that primarily provide visualization, the present system embeds automated billing and enforcement mechanisms within the same architecture. In the context of rental property management, the automated computation of bills, scheduled deadline monitoring, and programmed cutoff logic support administrative efficiency and reduce manual workload. The modular hardware configuration and use of commercially available components contribute to cost-effectiveness, while the scalable architecture allows expansion for multi-unit deployment. These combined features demonstrate operational efficiency, economic feasibility, and adaptability for small-scale residential energy management environments.

CONCLUSIONS

The energy monitoring device was successfully designed, developed, and evaluated using a structured developmental approach. The constructed prototype demonstrated high functional performance, achieving a 100% success rate across core operational features, including SMS command execution, energy rate modification, automated billing generation, and cutoff control. Efficiency testing showed that the system achieved a mean SMS transmission time of 26.4 seconds, which was statistically lower than the 32.7-second benchmark, indicating improved communication responsiveness. Reliability analysis further confirmed that device-based energy measurements and automated billing computations were statistically

consistent with reference submeter readings and manual calculations. These findings demonstrate that the integrated architecture combining real-time monitoring, automated billing computation, SMS-based notification, and programmable cutoff control can operate reliably in a residential energy management environment. The modular hardware configuration and use of commercially available microcontroller components indicate the potential for practical deployment in small multi-unit residential settings, although a detailed cost analysis is recommended for future studies to quantify economic advantages.

RECOMMENDATIONS

Future work may focus on further improving the scalability and functionality of the developed system. First, the system may be extended through cloud-based data storage and analytics to complement the existing Wi-Fi dashboard and enable long-term consumption analysis and centralized monitoring across multiple devices. Second, the architecture may be expanded to support multi-unit monitoring within a single controller platform, allowing landlords to manage several rental units through one integrated system. Third, integration with digital payment or mobile payment gateways may allow automated confirmation of tenant payments and real-time billing updates. Fourth, pilot deployment in actual residential rental environments is recommended to evaluate long-term operational stability and user acceptance under real usage conditions. Finally, the prototype may be enhanced with industrial-grade enclosure design and improved electrical protection mechanisms to ensure durability, safety compliance, and suitability for extended field deployment.

DECLARATION

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Credit Authorship Contribution Statement

Allea J-R F. Castro contributed to conceptualization, system design, prototype development, data collection, statistical analysis, software programming, and preparation of the original manuscript draft. **Remy G. Tamson** contributed to methodology validation, technical supervision, system evaluation, manuscript review, and editing.

Ethical Statement

The authors confirm that this research was conducted in full compliance with the ethical standards set by the International Journal of Engineering Innovation and Dissemination (IJEID). All participants provided informed consent prior to their involvement, and approval was obtained from the relevant educational authorities. The study adhered to principles of transparency, confidentiality, and academic integrity, with all data reported honestly and all sources properly cited. This study involved the development and testing of an electronic prototype device and did not involve human participants, animals, or personal data. All experimental procedures were conducted using electrical equipment and laboratory testing environments that followed standard safety practices for residential electrical systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

The authors declare that the data supporting the findings of this study will be made available upon reasonable request.

AI Usage Disclosure

This manuscript utilized Grammarly and Gemini AI for language refinement and editorial suggestions. Grammarly was used to enhance grammar, clarity, and readability, while Gemini AI provided support in rephrasing and improving sentence structure. These tools were not used for generating original content, conducting data analysis, or interpreting research findings. The authors retain full responsibility for the scholarly integrity, originality, and intellectual contribution of this work.

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