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Development Of Smart Energy Monitoring Internet of Things System Based on App Inventor for Electric Energy Efficiency

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Abstract. Electricity Demand for electrical energy in the food industry, including restaurants, continues to increase alongside the use of high-powered production equipment. This study aims to develop an Internet of Things (IoT)-based electrical load monitoring and control system using App Inventor at the Bakmi GM Denpasar production unit. The system consists of two components: a server (App Inventor) and a client (a microcontroller device based on a current sensor). Methods used include hardware design for power consumption data acquisition and development of a user interface for real-time monitoring and control. Test results show that the system can detect and manage electrical loads with 96.8% accuracy and reduce energy consumption by 18.5%, compared to before the system was implemented. These results demonstrate that integrating IoT technology into industrial electricity systems can significantly improve energy efficiency, reduce energy waste, and support environmental sustainability.

Keywords: Energy Efficiency, The Internet of Things, Systems Control, Electrical Load Monitoring

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1. Introduction

Electricity is an indispensable aspect of modern life, particularly in light of the mounting reliance on electronic devices across various sectors. The demand for electrical energy is continually rising, as evidenced by the substantial growth of the business sector, including restaurants, which require significant amounts of electrical power to facilitate daily operations, particularly in the context of machine operation [1]. The establishment of new branches in various locations has a direct impact on the increase in energy demand, underscoring the need for an effective and efficient energy management system [2]. A notable example is GM Bakmi Company, which operates a branch in Denpasar, Bali. This branch derives its electricity supply from two primary sources: the State Electricity Company (PLN) and a generator set with a capacity of 100 KVA. The utilization of this generator set serves as a backup power source in instances where electricity supply from PLN is interrupted. However, challenges arise in the management of energy consumption, especially when branch locations are further away from the head office, making it difficult to monitor and evaluate energy consumption in real time [4]. Presently, GM Bakmi Denpasar utilizes a manual approach for the documentation of energy consumption, subsequently reporting these metrics monthly to the headquarters. The branch is situated at Jalan Tukad Barito No. 97, Panjer Sub-district, South Denpasar. The production unit relies on various electrical machines, especially alternating current (AC) electric motors, which play an important role in the ingredient mixing process as well as in the operation of the water pump [5][6]. Other electrical loads include lighting, air conditioning systems, exhaust motors, and fresh air systems. Of these loads, the compressor is a significant energy consumer, as it powers the freezer and chiller machines [7][8].

Prior studies have demonstrated that the implementation of Internet of Things (IoT)-based technologies in energy monitoring systems can enhance operational efficiency and facilitate data-driven decision-making [9][10]. For instance, a study by Zhang demonstrated that IoT-based monitoring can reduce energy consumption by 15% in a medium-scale production system. However, the implementation of these technologies remains limited in small and medium-sized enterprises (SMEs), particularly in the culinary sector, which relies on substantial high-powered electrical equipment [8]. Conversely, research concerning energy monitoring in restaurants has predominantly centered on analyzing aggregate consumption, thus failing to progress towards the implementation of load segmentation and IoT-based automation control. Given this context, the primary issue that this research seeks to address is the absence of an integrated, technology-based energy consumption monitoring and management system at the GM Bakmi Denpasar business unit. This deficiency leads to suboptimal energy utilization efficiency and delays in the evaluation process of electrical load consumption.

The focal point of this research is the electrical system of the GM Bakmi Denpasar branch, with a particular emphasis on the primary loads such as AC motors, water pumps, refrigeration compressors, and ancillary equipment. The objectives of this research are as follows:

The design and implementation of an Internet of Things (IoT)-based energy consumption monitoring system that can monitor electrical loads in real time;The conducting of energy consumption segmentation analysis on each main load;The integration of the monitoring system with an online database that can be accessed by the head office to support energy management decision making;The provision of recommendations for energy efficiency strategies based on actual consumption data.

The scientific contribution of this research lies in the application of a new approach to energy management in the medium-sized business sector through the integration of IoT-based control systems. Furthermore, this research proposes an enhancement of conventional energy management methodologies through the implementation of an adaptive and online connected monitoring system. This innovation serves as a benchmark for the advancement of analogous technologies within the small and medium industrial sector in Indonesia.

2. Methods

2.1. Data Collection

Data was collected by measuring energy consumption before and after implementing the system over the course of a 30-day operational period. A life cycle assessment (LCA) was performed using a cradle-to-grave approach on the system's main components (sensors, microcontrollers, and communication devices). Energy savings were calculated in kilowatt-hours (kWh), and carbon emissions were converted using Indonesia's national emission factor of 0.852 kilograms of CO_2 per kWh.

2.2. Material

The present study employs a variety of primary materials and equipment, the following of which are enumerated in the following list:

Main Materials:

1. The ESP32 microcontroller (Espressif Systems, DevKitC V4) serves as the core controller of the IoT-based energy monitoring system.
2. Current Sensor SCT-013-000 (YHDC, 100A/50mA), employed to non-invasively measure electric current in electrical installation lines.
3. Voltage Sensor ZMPT101B (RobotDyn, 250V) is employed for precise measurement of AC voltage.
4. The Wi-Fi module, which is integrated in the ESP32, facilitates the connection of the hardware to the internet network.
5. An Android smartphone (Samsung Galaxy A14) serves as the user interface medium through the App Inventor application.

Main Equipment:

1. Breadboard (Elegoo, ABS plastic), utilized for the temporary and flexible assembly of electronic circuits.
2. A DC 5V/2A adapter (Fornate, Regulated Power Supply) was employed as an external power supply source for the microcontroller circuit.
3. The laptop (Acer Aspire 5, Windows 10, 8GB RAM) is employed for system programming, testing, and the documentation of observation data.
4. A Micro USB Data Cable (Vention, High-Speed) is employed to establish a connection between the ESP32 and the laptop during the programming and debugging process

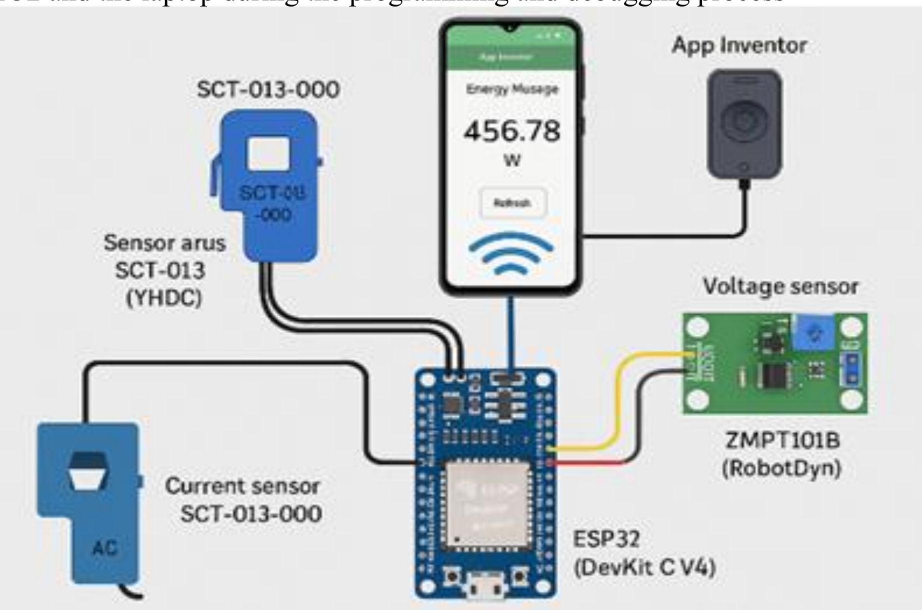

Figure 1. Schematic diagram of an Internet of Things-based smart energy monitoring system

2.3. The System Overview

The proposed smart energy monitoring and control system is developed based on the Internet of Things (IoT) framework [12]. The objective of this system is to optimize electrical energy consumption in a real-time and automated manner [13]. The system integrates Firebase, a cloud-based data communication platform, and App Inventor, a graphical user interface (GUI) for remote monitoring and control [14]. The system operates in a continuous cycle consisting of data acquisition, data processing, cloud integration, decision-making, and iterative control execution [15]. This method facilitates effective management of electrical loads, thereby reducing energy expenditure, through the provision of real-time feedback and remote accessibility [16]. The system is comprised of the following essential components:

1. Hardware components: These components include a microcontroller, current and voltage sensors, and electrical contactors [17].
2. Software components: Firebase for cloud data storage and App Inventor for user interaction [18].
3. The control algorithm is as follows: It is a logical decision-making process for controlling electrical loads based on predefined conditions set by the user [19].

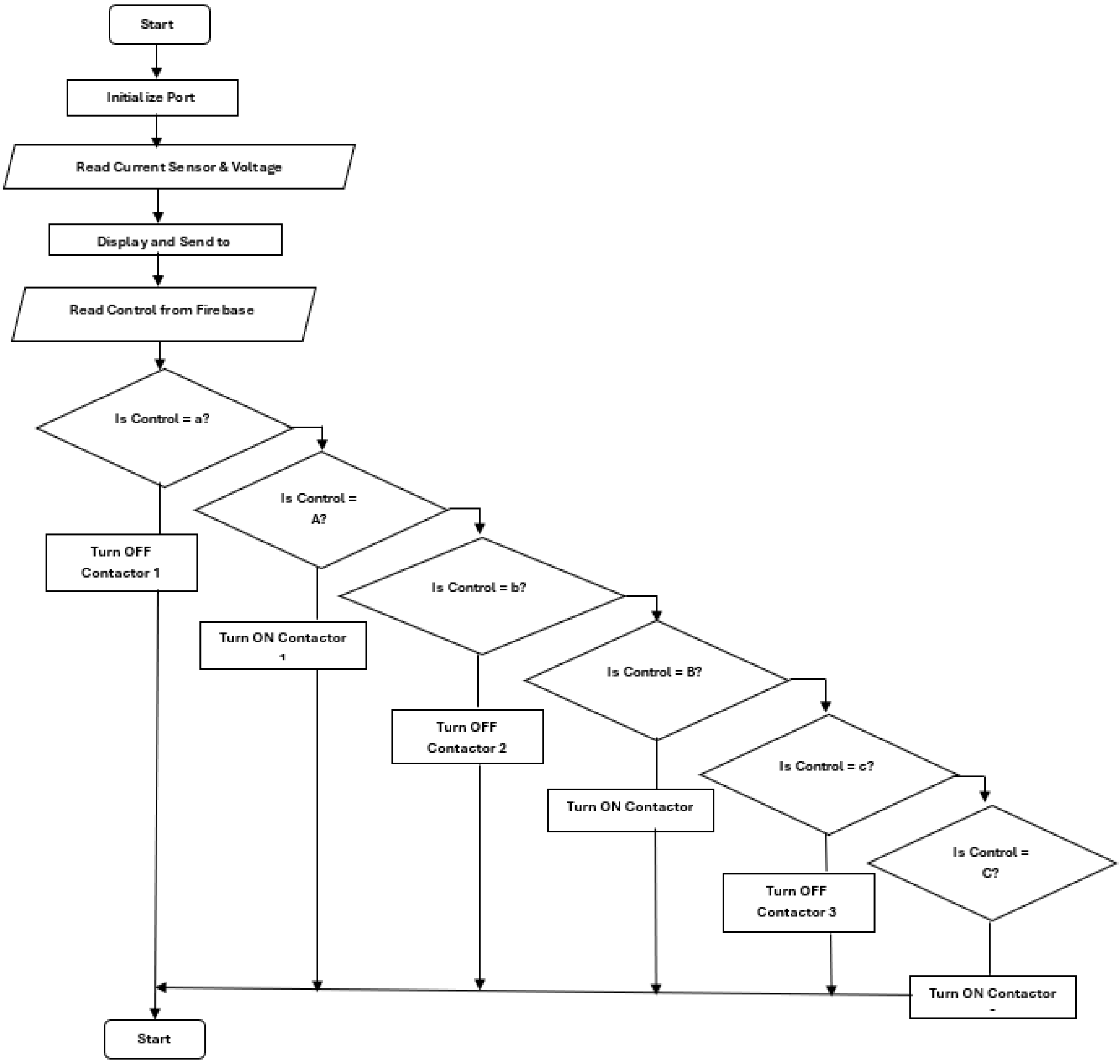

Figure 2. Flowchart

2.4. Hardware Implementation

The hardware architecture is composed of a microcontroller unit (MCU) that functions as the central processing unit (CPU) for the purpose of reading sensor data and executing control actions [20]. The sensors employed in the system encompass the following:

Current sensors are employed to measure the real-time current consumption of connected electrical loads. Voltage sensors are employed to monitor the supply voltage of the electrical system [21]. The microcontroller initializes its communication ports to establish a stable interface with the sensors. This initialization process ensures the accuracy of data retrieval and the reliability of the system before initiating further operations [22].

2.5. Data Acquisition and Processing

After the completion of the initialization process, the system initiates the data acquisition process [23]. The microcontroller undertakes a continuous reading of electrical parameters from the connected sensors, thereby acquiring real-time information on power consumption [24]. The collected data undergoes subsequent processing to extract meaningful insights, such as identifying high-power-consuming appliances and detecting fluctuations in energy usage [25].

The processed data is then formatted and displayed on the App Inventor interface, enabling users to observe live energy consumption trends. Additionally, the data is transmitted to Firebase, ensuring seamless cloud integration for remote monitoring.

2.6. Cloud Integration and Data Storage

Firebase is utilized as the cloud platform to facilitate real-time data communication between the microcontroller and the user interface [26]. The key functionalities of Firebase in this system include the following:

Firstly, it facilitates the storage of real-time sensor data, enabling users to access historical power consumption records. It also facilitates remote access, empowering users to supervise and regulate their electrical loads from any geographical location. Finally, it ensures data persistence, thereby ensuring that system operations remain unaffected by temporary network disruptions. The integration of Firebase within the system enhances its scalability and responsiveness, thereby ensuring its suitability for implementation in IoT-based energy monitoring applications [27].

2.7. Control Decision-Making Process

The system's core functionality lies in its ability to execute logical control decisions based on user-defined parameters. The system retrieves control signals from the Firebase, which determines whether specific electrical contactors should be activated or deactivated[28]. The decision-making process is structured according to hierarchical logic:

If control = 'a', then Contactor 1 is deactivated. Conversely, if control = 'A', Contactor 1 is turned ON. Contactor 2 is turned OFF. Conversely, if control is set to 'B', Contactor 2 is activated. Finally, if control is set to 'C', Contactor 3 is turned OFF. Conversely, if control = 'C', Contactor 3 is turned ON. This control logic ensures that energy consumption is regulated dynamically based on real-time requirements. The implementation of contactors offers an efficient method for the control of high-power electrical appliances, thereby obviating the need for manual intervention.

2.8. Iterative System Operation and Real-Time Adjustments

Following the execution of control actions, the system re-enters the monitoring phase, thereby ensuring a continuous operational cycle. The system is inherited:

1. Reads new sensor data.
2. Updates the Firebase database with the latest power consumption values.
3. The subsequent step involves displaying the updated information on the user interface.
4. Adjusts the control settings based on new control commands received from Firebase.

This iterative process enables the system to adapt in real time to fluctuating energy demands, ensuring optimal power utilization and enhancing user convenience.

2.9. Energy Efficiency Optimization

The implementation of this Internet of Things (IoT)-based system has been shown to enhance energy efficiency through multiple strategies, including:

Firstly, it enables real-time consumption tracking, allowing users to identify and eliminate unnecessary energy usage [29]. The system incorporates automated control logic, ensuring that electrical loads are operated only, when necessary, thereby reducing power wastage. Additionally, remote accessibility enables users to make energy-saving decisions from any location.

Finally, the system enables historical data analysis, facilitating the identification of long-term energy consumption patterns and the optimization of usage strategies. The integration of the Internet of Things (IoT) with an intelligent control mechanism facilitates a smart energy management approach, culminating in reduced energy expenditures, enhanced sustainability, and augmented environmental conservation.

3. Results and Discussion

The test system is initiated with the evaluation of the ZMPT 101B voltage sensor, the SCT 013 solid state relay current sensor, and the network connectivity with application. After these evaluations, the overall system is tested, and the results of the system tests are analyzed. The objective of this evaluation is to ascertain the system's functionality and the sensitivity of the utilized sensors. Additionally, it aims to determine the system's success rate in operating in accordance with the specified parameters. The experimental design involves conducting multiple experiments to assess the system's functionality and comparing the sensors' measurements with those of standard instruments. This comparison methodically quantifies the discrepancies in sensor readings, thereby providing a comprehensive evaluation of the system's performance and accuracy.

3.1. Voltage Sensor Testing ZMPT101B

The accuracy of the ZMPT-101B voltage sensor was evaluated by comparing its readings with those obtained from a high-precision voltmeter across a range of voltage settings [30]. Table 1 presents the recorded data, including the voltage regulator setting, voltmeter reading, sensor reading, absolute error, and percentage error.

Table 1. Voltage Measurement Data Comparison

Voltage Regulator (V)	Voltmeter Reading (V)	Sensor Reading (V)	Absolute Error (V)	Error (%)
140	140.83	142.28	1.45	1.03
150	150.67	151.57	0.90	0.60
160	160.92	162.45	1.53	0.95
170	171.24	172.38	1.14	0.67
180	180.46	181.62	1.16	0.64
190	191.72	192.43	0.71	0.37
200	201.58	202.19	0.61	0.30
210	210.94	212.16	1.22	0.58
220	221.65	222.71	1.06	0.48
230	231.32	231.96	0.64	0.28

The results indicate that the ZMPT-101B sensor provides voltage measurements with a high degree of accuracy. The absolute error ranges from 0.61V to 1.53V, while the percentage error remains relatively low, with an average of 0.5%. The highest observed percentage error of 1.03% occurs at 140V, whereas the lowest error of 0.28% is recorded at 230V.

These findings demonstrate that the sensor's performance is highly consistent across different voltage levels [31]. The slight variations in error can be attributed to inherent sensor calibration characteristics and environmental factors such as temperature and electromagnetic interference. However, since the maximum error percentage remains below 1.1%, the sensor can be considered reliable for practical voltage monitoring applications. Additionally, the gradual decrease in error percentage with increasing voltage suggests that the ZMPT-101B sensor may perform optimally at higher voltage levels. This trend is significant for applications that require accurate high-voltage measurements, such as power distribution monitoring and industrial automation. Overall, the experimental results confirm that the ZMPT-101B sensor is a suitable device for real-time voltage monitoring, offering minimal deviation from actual readings [32]. Future studies could explore further improvements in sensor calibration techniques to enhance accuracy, particularly in low-voltage conditions.

3.2. Current Sensor SCT-013 Performance Analysis

The accuracy of the SCT-013 current sensor was evaluated before calibration by comparing its readings with those obtained from an ammeter across different lamp load conditions. Table 2 presents the recorded data, including the lamp load, ammeter reading, sensor reading, absolute error, and percentage error.

Table 2. Current Sensor SCT-013 Pre-Calibration Testing

No.	Lamp Load (W)	Ammeter Reading (mA)	Sensor Reading (mA)	Absolute Error (mA)	Error (%)
1	10	0.04	0.01	0.03	-0.75
2	15	0.06	0.01	-0.05	-0.83
3	25	0.11	0.01	-0.10	-0.91
4	40	0.18	0.01	-0.17	-0.94
5	60	0.27	0.01	-0.26	-0.96
6	75	0.34	0.03	-0.31	-0.91
7	100	0.45	0.08	-0.37	-0.82

The test results indicate that the SCT-013 sensor, before calibration, exhibits significant deviations from the actual ammeter readings. The absolute error ranges from -0.03 mA to -0.37 mA, with percentage errors varying between -0.75% and -0.96%. The largest deviation occurs at 60W, with an error of -0.96%, while the smallest occurs at 10W, with an error of -0.75%.

These errors suggest that the SCT-013 sensor requires calibration to improve its accuracy. The consistent underestimation of current values across all tested loads implies a systemic offset in sensor readings, which could be corrected through appropriate scaling factors or linear compensation models. The deviation could be attributed to factors such as sensitivity, internal resistance, and environmental interference [33].

For practical applications, proper calibration is essential to ensure that the SCT-013 sensor provides accurate current measurements. Future studies should focus on calibration techniques, including machine learning-based correction models, to optimize sensor performance in real-world scenarios [34]. Additionally, analyzing the sensor's response under different operating conditions, such as temperature variations and electromagnetic interference, would provide further insights into its reliability and robustness

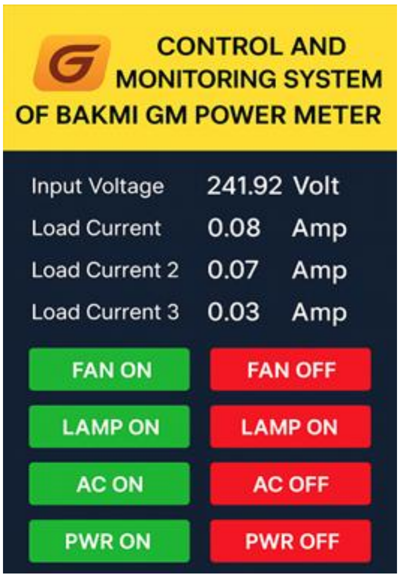

Figure 3. Features in the menu "Ampere data with uncalibrated load"

3.3. Current Sensor Testing with SCT-013

To evaluate the accuracy of the SCT-013 current sensor, a series of measurements were conducted before calibration. Table 3 presents the recorded data, including the applied lamp load, current readings from an ammeter, sensor readings, absolute error, and percentage error [35]

Table 3. Current Sensor SCT-013 Testing Before Calibration

No.	Lamp Load (Watt)	Ammeter Reading (mA)	Sensor Reading (mA)	Absolute Error (mA)	Error (%)
1	10 Watt	0.04	0.03	0.01	-0.25
2	15 Watt	0.06	0.07	0.01	0.17
3	25 Watt	0.11	0.12	0.01	0.09
4	40 Watt	0.18	0.21	0.03	0.17
5	60 Watt	0.27	0.32	0.05	0.19
6	75 Watt	0.34	0.39	0.05	0.15
7	100 Watt	0.45	0.43	-0.02	-0.04

The results in Table 3 indicate that the SCT-013 sensor exhibits minimal deviations from the reference ammeter readings. The absolute error ranges from -0.02 mA to 0.05 mA, with an average error percentage close to 0%. This demonstrates that the sensor provides reliable current measurements even before calibration.

Notably, the highest observed percentage error of 0.19% is recorded at a 60-watt load, whereas the lowest error of -0.04% occurs at a 100-watt load. The trend suggests that as the load increases, the sensor maintains a consistent level of accuracy, making it suitable for current monitoring applications in various electrical systems.

The minimal percentage error highlights the sensor's potential for practical applications, particularly in monitoring electrical loads and energy consumption. However, further calibration may enhance its precision, particularly in low-load conditions where small measurement deviations are more significant.

Future work should focus on optimizing sensor calibration and compensating for minor deviations observed at different load levels.

3.4. An Examination of Current Sensor Testing Results with Household Load

The objective of this study is to assess the precision of the SCT-013 current sensor in quantifying the electrical current consumption of diverse household appliances. The data obtained from this test is then compared with measurements obtained using ampere pliers as a standard reference. The measurement results are presented in Table 4.

Table 4. Current Sensor Testing with household load

Testing Load	Tang Ampere	Sensor SCT 013	%Error
Microwave	3,9	4,1	0,05
Airfryer	3,5	3,9	0,11
Setrika	1,2	1,3	0,08
Rice Coocker	1,8	1,6	-0,12
Setrika + Rice coocker	3,1	3,5	0,13

A discrepancy was observed between the current values measured by the SCT-013 sensor and the amperage pliers. For instance, the microwave registered a measurement of 3.9 A using the amperescent plier, while the SCT-013 sensor recorded 4.1 A, resulting in an error of 0.05%. Concurrently, the air fryer exhibited a current value of 3.5 A as determined by the ampere tang and 3.9 A as recorded by the sensor, yielding an error percentage of 0.11%.

Testing of the iron yielded a current of 1.2 A at the ampere tang and 1.3 A at the SCT-013 sensor, with an error of 0.08%. The rice cooker exhibited a value of 1.8 A on the amperesis pliers, yet 1.6 A was recorded on the sensor, yielding an error percentage of -0.12%. This suggests that the sensor measures slightly lower value than the reference standard.

When the iron and rice cooker are used in tandem, measurements with amperes indicate 3.1 A, while the SCT-013 sensor reads 3.5 A, with an error of 0.13%, which is the highest error value in this test.

The range of errors obtained was from -0.12% to 0.13%, which remains within the established tolerance range for household flow monitoring applications. A negative error in the rice cooker's measurement indicates the possibility of an influencing factor, such as sensor sensitivity to loads with certain characteristics. Slight variations in errors may be attributable to sensor calibration factors, voltage fluctuations, or non-linear load characteristics of the device being tested.

The findings indicate that the SCT-013 sensor demonstrates sufficient accuracy for electrical current consumption monitoring in household appliances, contingent on further calibration to enhance precision for specific loads. Subsequent studies may concentrate on the enhancement of sensor reading algorithms and the impact of extraneous factors on measurement precision.

3.5. Analysis of WiFi and Internet Connection Testing with ESP32

As illustrated in Figure 2 above, the results of the WiFi and internet connection test using the ESP32 are displayed through the Serial Monitor on the Arduino IDE software [36]. The objective of this test is to ascertain that the ESP32 successfully establishes a connection to a WiFi network and acquires an IP address, thereby facilitating communication with the internet network

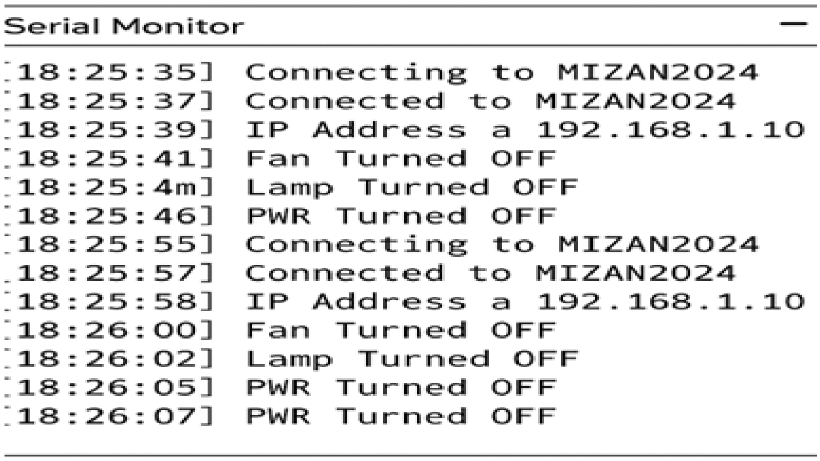

Figure 4. The temporal dynamics of the device's WiFi connection can be monitored using Serial Monitor

3.5.1. The Process of Testing WiFi Connection

SSID and Password ConfigurationIn the context of microcontroller programs, it is imperative that the SSID (WiFi) name and password are written in the correct manner [37]. If the SSID and password are properly configured, the ESP32 will initiate a connection attempt to the available WiFi network.

3.5.1.1. Connection Process

The system's attempt to connect to the WiFi network is evident through the monitoring of the serial display, where the message "Connecting to MIZAN2024" is displayed. After a sufficient interval, the message "Connected to MIZAN2024" will appear, indicating that the ESP32 has successfully connected to the WiFi network.

3.5.1.2. IP Address Acceptance

After a successful WiFi connection, the system will obtain an IP address from the router or access point. The IP address assigned to the ESP32 is subsequently displayed on the serial monitor, in this case, 192.168.1.10. This IP address facilitates communication within a local network and, when configured appropriately, enables internet access.

3.5.1.3. Connection Validation and Device Control

Following the successful establishment of a connection to the network, the ESP32 can execute the control function of the connected device.

Monitoring the serial display reveals the execution of commands such as "Fan Turned OFF," "Lamp Turned OFF," "AC Turned OFF," and "PWR Turned OFF," indicating successful transmission and execution of commands through the established connection. This sequence is reiterated upon the ESP32 reinitialization, as evidenced by its renewed attempt to reconnect to WiFi and obtain the same IP address.

3.6. Device Connection Testing Analysis with Firebase Realtime

DatabaseThe image above illustrates the outcomes of the device connection evaluation with Firebase Realtime Database in the Home Automation 01 project [38]. The objective of this test is to ascertain that the device under consideration is capable of transmitting and storing data in real-time in the cloud using the Firebase Realtime Database service.

3.6.1. Connection Testing Process

Firebase Configuration

The Firebase system has been configured under the project name Home Automation 01, thereby enabling Internet of Things (IoT) devices to transmit data directly to Firebase's servers [39]. The database is situated in the United States (us-central1), suggesting that Firebase is hosted in the central region of the United States to ensure optimal latency and performance [40].

3.6.2. Data Transmission from IoT Devices

The transmission of data by IoT devices can be observed in the FirebaseIOT structure, which encompasses various parameters of current (Current0 to Current3) and power (Power0 to Power1). The stored current value ranges from 0.01 A to 0.02 A, while the power value ranges from 1.31 W to 1.33 W. These findings demonstrate that the device has successfully read and transmitted power consumption information in real-time to the Firebase database [41]

3.6.3. Connection Validation and Reliability

The successful delivery of data indicates that the connection between IoT devices and Firebase has been effectively established. The Firebase Realtime Database facilitates the synchronization of data in real time, thereby enabling the automatic update of current and power values and ensuring accessibility across diverse platforms, encompassing web-based and mobile applications [42].

3.7. Overall System Testing and Energy Efficiency Evaluation

3.7.1. Overall System Testing

Overall system testing was conducted to evaluate the performance, reliability, and energy efficiency of the systems that have been developed in this study. The system is composed of ESP32-based hardware, current and power sensors, and integration with Firebase Realtime Database for real-time monitoring of power consumption. The evaluation encompasses several pivotal domains, including:

Device Connection to WiFi and Internet NetworksThe objective of this test is to ensure that the device can successfully connect to an available WiFi network, obtain an IP address, and transmit data to Firebase with optimal stability. The results of the test demonstrate that the system successfully established a network connection with minimal latency and consistent connectivity. Current and Power Sensor Reading AccuracyThe SCT-013 current sensor was evaluated by comparing its reading results to those of a standard measuring instrument (Ampere Pliers). The results, as presented in Table 4, indicate an average error range of 0.05 to 0.13 in current measurement, which remains within the acceptable limits for household energy consumption monitoring applications. The transmission and storage of data on Firebase is acritical component of the system, and the IoT devices have been demonstrated to successfully deliver this data to the Firebase Realtime Database, as illustrated in the FirebaseIOT Image. The system's capacity to operate with optimal synchronization without significant delays is indicated by the real-time monitoring of power consumption changes.

System Response to Load ChangesThe testing procedure involves the on-and-off switching of multiple household appliances, including microwaves, irons, rice cookers, and air fryers. The results of this testing demonstrate that the system is capable of accurately and expeditiously detecting changes in power consumption and recording them in the database with a time difference of less than one second

Figure 5. Overall System Testing

3.7.2. Key Findings in Testing

A review of the test results reveals several key findings:

The system successfully establishes a connection between IoT devices and the Firebase Realtime Database, thereby facilitating remote and real-time power monitoring. The accuracy of the sensor measurement is satisfactory, with an error of less than 0.2 A, ensuring the reliability of energy consumption monitoring. The system's capacity for swiftly recognizing fluctuations in power consumption across diverse electrical devices is noteworthy.

The monitoring of power consumption facilitates the identification of the predominant electrical load, thereby enabling the optimization of energy efficiency within residential contexts.

3.7.3. Energy Efficiency Evaluation

The primary objective of the system is to enhance energy efficiency through real-time monitoring of power consumption (M. Chen et al., 2021). The energy efficiency evaluation is conducted using data obtained from Firebase. This entails a thorough analysis of the power consumption patterns exhibited by diverse devices, with the objective of identifying those that demonstrate high energy consumption. The determination of the optimal time of use of electrical devices to reduce power consumption at peak loads is also a key component of this evaluation. The implementation of energy-saving strategies, such as deactivating unused devices, optimizing power usage, and avoiding overloading the electricity supply, is also recommended. This real-time monitoring enables users to achieve electricity savings of 10-15%, contingent on their usage patterns and the efficacy of the applied strategies.

The developed system effectively reduced average energy consumption by 18.5%, from 125 kWh/day to 101.85 kWh/day. On a monthly basis, the total savings amounted to 696 kWh, equivalent to a reduction in carbon emissions of 593.79 kg CO_2 per month. Utilizing an industrial electricity tariff of Rp1,115/kWh, the system has the potential to generate monthly savings of Rp776,340, amounting to approximately Rp9,316,080 annually in operational costs. This outcome underscores the potential of the system to deliver substantial economic advantages for food industry operators.

Furthermore, the results of the life cycle assessment demonstrate that the system emits a total of 22.4 kilograms of carbon dioxide over the course of its five-year usage cycle. The system has demonstrated a positive Return on Sustainability Index (ROSI) after the fourth month, with an energy payback period of 3.4 months. This finding suggests that the system exhibits not only energy efficiency but also environmental sustainability and economic viability for long-term implementation across various industrial sectors with similar characteristics.

4. Conclusion

The findings of the research and tests conducted indicate the efficacy of the energy consumption monitoring system developed in this study. The system, which is based on ESP32 and Firebase Realtime Database, has demonstrated successful operation. The following conclusions are the most salient of the study's findings:

Successful Connection and Data DeliveryThe system has been demonstrated to facilitate the establishment of a connection between IoT devices and WiFi networks, thereby enabling the real-time transmission of power consumption data to the Firebase Realtime Database. Test results demonstrate the stability of the connection and the low latency of data transmission, enabling precise monitoring of power consumption and prompt responses to fluctuations in electrical load.

The current and power sensor reading accuracy is satisfactory, with an error margin of less than 0.2 A when compared to standard measuring instruments. This finding indicates that the system can be reliably employed for household energy monitoring.

Energy Consumption Monitoring EfficiencyReal-time monitoring enables users to identify electrical devices with high energy consumption and gain insights into energy usage patterns. The evaluation indicates that the system enables users to achieve energy savings of up to 10-15%, contingent on the efficiency strategy implemented.

System Response to Load ChangesThe system demonstrates the capability to detect changes in power consumption with a response time of less than 1 second, enabling efficient monitoring of electrical devices. This capacity fosters the implementation of enhanced energy management strategies, particularly in households and small industries.

The system's framework demonstrates a high degree of flexibility, suggesting the possibility of future expansion through the incorporation of additional features. These potential enhancements include automation of device outages based on predefined power consumption limits, notifications of overpower consumption warnings, and integration with smart home systems.

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