INTERNATIONAL JOURNAL OF ACADEMIC RESEARCH IN BUSINESS & SOCIAL SCIENCES

Vol 14, Issue 12, (2024) E-ISSN: 2222-6990

IOT-Based Cost-Effective Energy Meter Monitoring System for Smart Home Applications: Design, Implementation, and Analysis

Eliyana Ruslan[1], Sahazati Md Rozali[2], Ernie Che Mid[3], Dayanasari Abdul Hadi[1], Siti Halma Johari[1]

[1]Fakulti Teknologi dan Kejuruteraan Elektronik dan Komputer, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia, [2]Fakulti Teknologi dan Kejuruteraan Elektrik, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia, [3]Fakulti Kejuruteraan & Teknologi Elektrik (FKTE), Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia

Corresponding Author Email: eliyana@utem.edu.my

To Link this Article: http://dx.doi.org/10.6007/IJARBSS/v14-i12/24398 DOI:10.6007/IJARBSS/v14-i12/24398

Published Date: 29 December 2024

Abstract

This research presents the design, implementation, and analysis of a cost-effective energy meter monitoring system utilizing Internet of Things (IoT) technology for smart home applications. The system aims to address the growing need for efficient energy management, particularly in student housing environments where energy consumption awareness is crucial. A novel approach that integrates NodeMCU ESP8266, PZEM-004T current sensor, and a custom-designed mobile application to provide real-time energy consumption data and remote- control capabilities is proposed. The methodology involves a comprehensive system design, hardware integration, and software development using Arduino IDE and MIT App Inventor. The experimental setup monitored energy consumption patterns over a week, analysing both daytime and nighttime usage. Results demonstrate the system's efficacy in tracking power consumption, with notable variations observed between weekdays and weekends. The implemented IoT solution successfully enabled remote monitoring and control of household appliances, potentially leading to significant energy savings. Data analysis revealed peak consumption periods and usage patterns, providing valuable insights for energy management strategies. This cost-effective solution shows promise in promoting energy conservation awareness among users, particularly students, and has potential applications in broader smart city initiatives for sustainable energy management.

Keywords: IoT, Smart Home Energy Management, Energy Consumption Analysis, Smart Grid Integration

Introduction

The advancement of Internet of Things (IoT) technology presents a transformative opportunity for energy management within smart homes. The development of a cost-effective energy meter monitoring system leveraging IoT is a pivotal innovation aimed at enhancing energy efficiency and reducing wastage. This research targets three core objectives: first, to develop a mobile application for real-time observation of energy consumption; second, to establish a monitoring system for initial meter readings via an application linked with hardware; and third to design and implement energy meter hardware that minimizes electrical energy wastage. Achieving these goals will offer a comprehensive solution for optimizing residential energy management, aligning with recent advancements in IoT technology and smart energy systems.

The increasing prevalence of IoT technology has fueled advancements in smart energy meters, which offer a range of features from energy tracking to automatic alerts for energy wastage. Several researchers have focused on the development and implementation of smart energy meters integrated with IoT. Govindarajan, Meikandasivam, Malathi, and Kiranmai (2020) presented a smart energy metering system using an Android mobile application that allows consumers to easily monitor their energy consumption, serving as a cost-effective alternative to traditional systems. Similarly, Avancini, Rodrigues, Rabêlo, Das, Kozlov, & Šolić (2020) developed an IoT-based smart energy meter designed for smart grids, emphasizing real-time data monitoring to ensure efficient energy consumption. Dass, Akhila, & Prasanjith (2023) also highlighted the role of IoT in improving smart meter functionalities, introducing an automated solution for energy monitoring to enhance user control over consumption patterns. Furthermore, other had proposed an IoT-enabled smart energy meter capable of providing detailed reports on energy usage, which can help users make informed decisions about their energy habits (Enugurti, Ambekar, Dethe, & Sadu, 2023).

The integration of IoT into smart energy meters also enables more advanced functionalities, such as energy theft detection and power quality monitoring. Kshirsagar and Kshirsagar (2021) presented an IoT-based energy meter that emphasizes cost efficiency while offering essential monitoring features. Jambi, Wong, Juwono, & Motalebi (2023) further delved into the security challenges that come with IoT-based energy meter systems, outlining the opportunities for secure energy monitoring in real-time settings. Meanwhile, Karthick, Raja, Nesamalar, & Chandrasekaran (2021) designed a compact IoT-based smart energy meter that addresses power quality issues and energy wastage, making it suitable for a wide range of applications. The works of de Sousa et al. (2023) and Selvan, Sivabalan, Ramesh, & Ragadeepa (2023) also emphasize real-time monitoring solutions, providing insights into both low-cost wireless meters and cloud storage integration for enhanced accessibility. Such systems enable not only efficient energy management but also ensure robust performance through continuous monitoring and real-time alerts.

Other significant advancements in IoT-based smart meters include automation and optimization to prevent energy wastage. Estibeiro (2022) introduced a system focused on real- time energy tracking and consumption control through IoT-based infrastructure. Jha, Pal, Sonawane, & Bhatia (2023) similarly proposed an automated smart meter system that incorporates real-time consumption alerts, offering a more intuitive interface for users to manage their electricity use. Research from Subhash, Balaji, Sanjana, Madhavan, & Siva

(2020) explored energy meter automation within IoT systems, focusing on improving energy tracking efficiency and reducing human intervention. Additionally, Islam, Talukder, Saima, Rimon, & Ali (2021) offered an IoT-enabled smart energy meter with a real-time tracking system, providing a comprehensive review of similar implementations aimed at reducing energy consumption and enhancing user awareness. These contributions highlight the crucial role IoT plays in automating energy usage monitoring, thus promoting energy savings.

Lastly, advancements in communication technologies and their integration with IoT-enabled energy meters have led to the development of highly functional and interconnected systems. Anand, Chaudhary, Mukherjee, & Yadav (2021) explored the use of GSM technology for theft detection and load control in energy meters, highlighting its potential in minimizing energy loss. Tahir, Bihani, & Tiwari (2022) discussed an Android-based system for energy metering, showcasing how mobile apps enhance user interaction and control over energy usage. Similarly, Sheeba et al. (2021) focused on real-time monitoring systems that integrate cloud-based storage for tracking energy consumption remotely. The design of such systems has been further optimized by researchers like Govindarajan, Meikandasivam, & Vijayakumar (2020), who emphasized energy monitoring in both residential and commercial settings. Additionally, Jha, Agrawal, & Rizwan (2020) contributed to the ongoing development of energy meters by introducing a data logger for more precise tracking of energy usage patterns. Meanwhile, Sharma, Bhajbhuje, Tajane, & Dharmik (2022) demonstrated the potential of smart automated meters to significantly reduce unnecessary energy consumption, making energy management more streamlined. The use of sensors and real-time tracking, as emphasized by Rajeshbabu, Mounika, Varalakshmi, Reddy, & Kumar (2023), further contributes to the overall goal of preventing energy wastage.

Methodology

The methodology of this study is centred on the development and integration of both hardware and software components to create an IoT-enabled energy monitoring system. The flowchart in Figure 1 depicts an electrical power monitoring system. It starts by setting a power limit, then continuously reads electrical data and loads devices. The system checks for tampering and excess power usage. If tampering is detected, it displays a warning. If power exceeds the limit, it notifies the user, controls appliances, and toggles loads. The process loops unless monitoring is stopped. This system aims to optimize energy use, prevent unauthorized access, and automate power management. It balances user control with automated responses, suggesting an application in smart home or building energy management. The flowchart emphasizes safety, efficiency, and user awareness in electrical consumption.

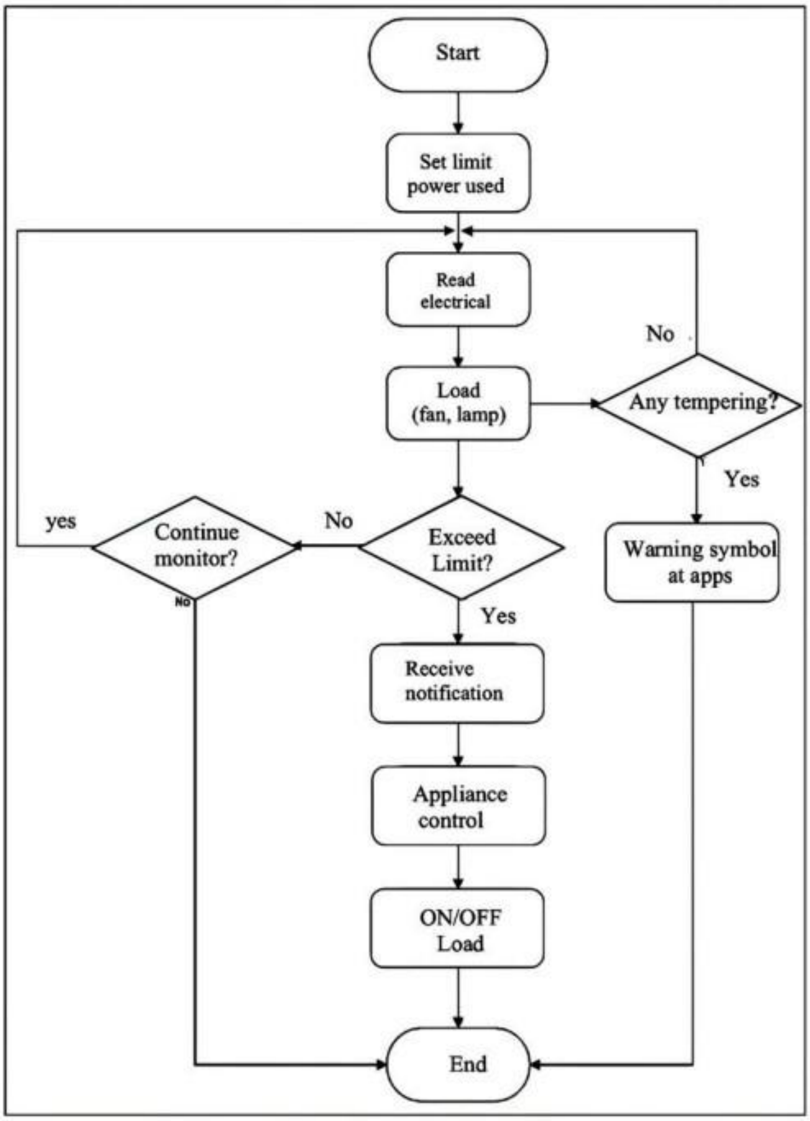

Figure 1: Block diagram of proposed method

Hardware Development: The system's core components include the NodeMCU ESP8266 microcontroller, PZEM-004T energy meter and other sensors such as the vibration sensor SW-420. The energy meter system measures voltage and current in real-time using the PZEM-004T sensor. The hardware development is detailed in Figure 2 and involves connecting the energy meter to the microcontroller, which is then linked to a mobile application via Wi-Fi.

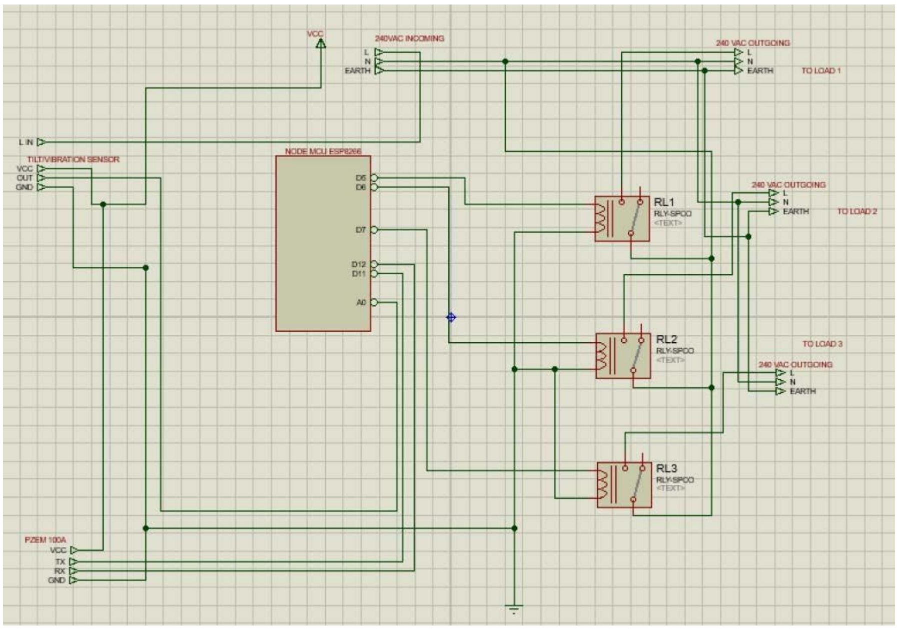

Figure 2: The architecture of hardware circuitry

Software Design: The mobile application was developed using MIT App Inventor, as depicted in Figures C and D. The app provides a user-friendly interface for real-time monitoring and control of household appliances. It was designed to monitor and manage energy consumption in real-time. Figure 3 is showing the "ENERGY METER STATUS", providing users with immediate access to crucial energy consumption data. Additionally, it shows the total energy usage in kWh. This interface is the main page of the mobile application.

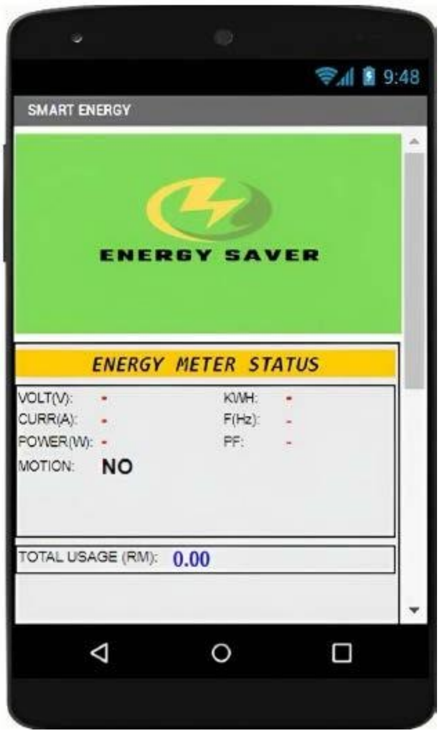

Figure 3: Design application using Mit Invertor

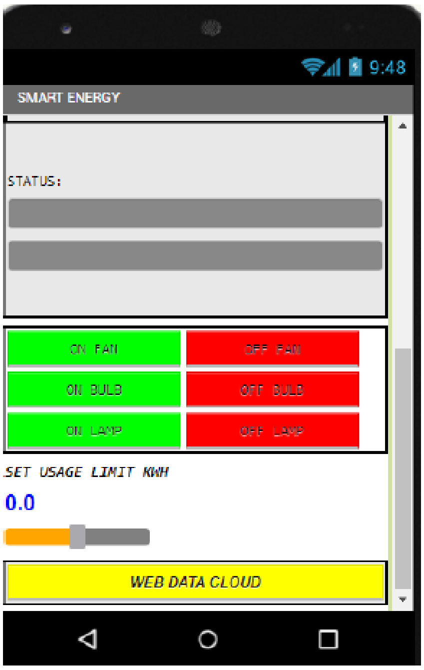

Figure 4: Design application for electrical appliances status

Figure 4 offers more interactive features for user control and detailed status information. It's showing the electrical appliances status. Multiple status indicators, likely representing different appliances or circuits, are shown as green (on/active) or red (off/inactive) buttons. A slider allows users to set their desired energy usage limit, giving them control over their consumption targets. A "WEB DATA CLOUD" button indicates cloud connectivity, suggesting that data can be synchronized, stored, or analysed online for more comprehensive energy management.

This design choice makes the app intuitive and easy to navigate, even for users who might not be tech-savvy. The application appears to be part of a larger smart energy system, likely connected to smart meters or IoT devices in the home or business. It empowers users to monitor their energy consumption patterns, set usage goals, and potentially control connected devices remotely. By providing real-time data and user-friendly controls, this app aims to promote energy awareness, facilitate cost savings, and encourage more sustainable energy use habits. The cloud connectivity feature suggests the possibility of accessing historical data, generating reports, or even participating in broader energy management programs or initiatives.

Data Collection: Data was collected over a one-week period, with power consumption recorded daily. The data was analysed to identify patterns in energy use and determine the effectiveness of the system.

Results and Discussion

The results section presents the data collected during the experimental phase, analysed through various graphs. Energy Consumption Analysis: To understand the total energy usage over a specified period, the system calculates energy by integrating the power consumption over time. This provides a more comprehensive understanding of cumulative energy use, beyond just instantaneous power measurements. Figure 5 shows the prototype design, while Figure 6 illustrate the power and billing data for a single day of fan usage. This figure indicates a direct correlation between power usage and the corresponding cost, emphasizing the system's capability to monitor and manage energy consumption effectively.

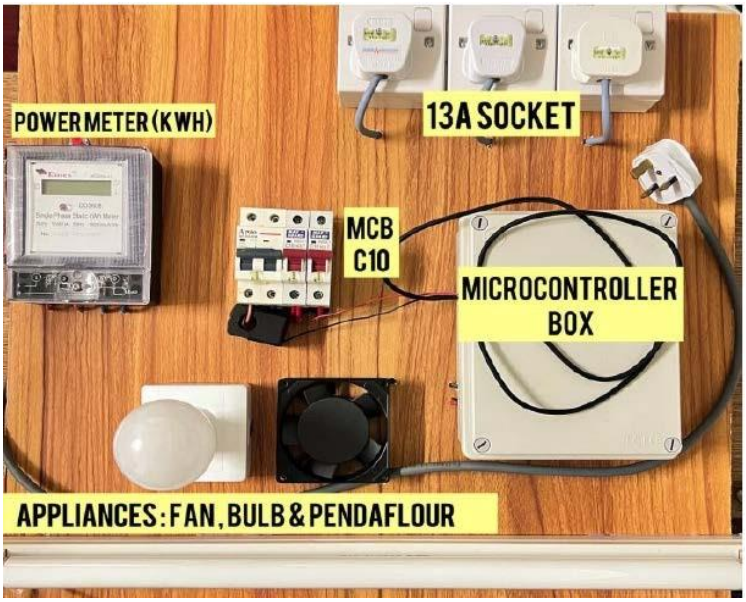

Figure 5: Energy Meter Monitoring System Prototype Design

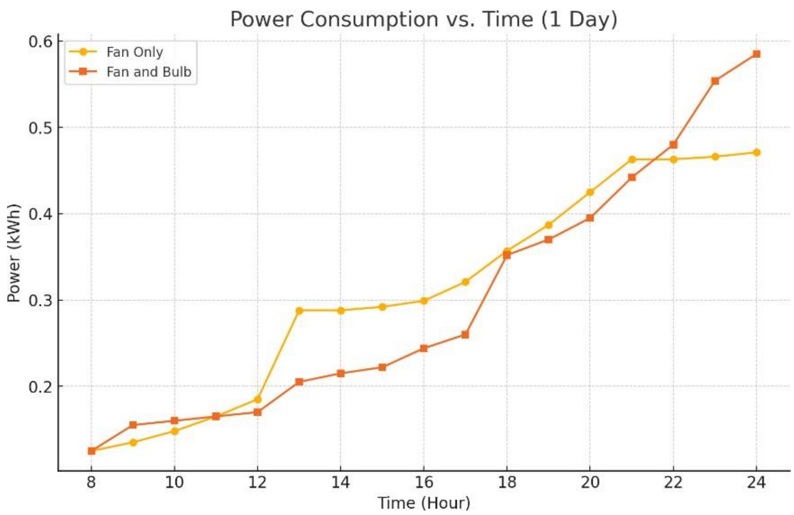

Figure 6: Daily Energy Consumption

Figure 6 provides insights into daily energy usage patterns under different appliance configurations. The analysis reveals that although the "Fan Only" configuration tends to consume more power in the later hours, the "Fan and Bulb" setup generally follows a similar trend with slight variations in consumption levels throughout the day. This information could be valuable for optimizing energy usage in smart meters and implementing demand-side management strategies.

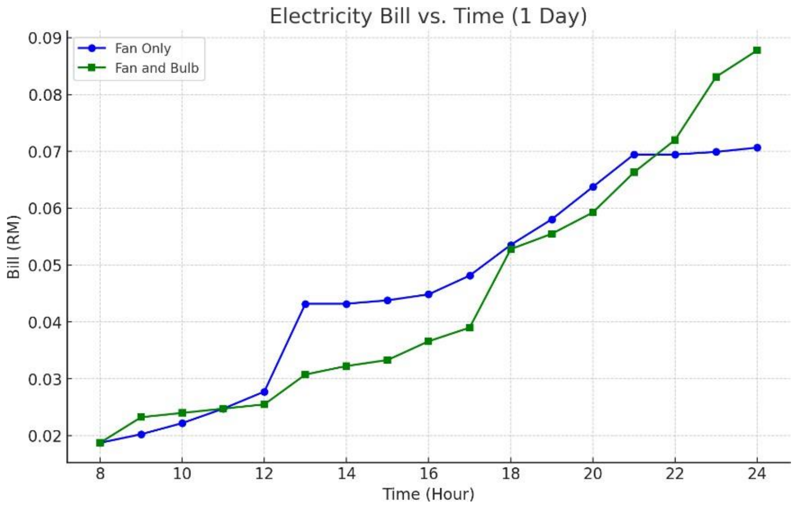

Figure 7: Daily Electricity Costs

Figure 7 demonstrates that electricity costs are more dependent on time of usage rather than the specific configuration, although the "Fan Only" setup consistently results in higher bills toward the latter part of the day. The comparative increase in the "Fan and Bulb" setup's cost is modest, suggesting that combined usage of appliances can be energy-efficient under certain conditions. These insights can assist in developing energy-efficient scheduling strategies for residential or commercial environments, particularly in systems utilizing smart energy meters for real-time billing.

Weekly Data Analysis: Table 1 and Figure 8 display the energy consumption data over a week, showing variations in daylight and night time usage. The analysis highlights the peak usage times and the effectiveness of the system in managing these peaks.

Table 1
The Data Collected for a Week

DAYS	DAYLIGHT POWER (KWH) USAGE OF FAN	NIGHT POWER (KWH) USAGE OF FAN & LAMP
MONDAY	7.225	10.120
TUESDAY	7.668	10.650
WEDNESDAY	7.985	11.550
THURSDAY	8.557	12.520
FRIDAY	9.225	13.650
SATURDAY	9.555	15.857
SUNDAY	9.832	18.215

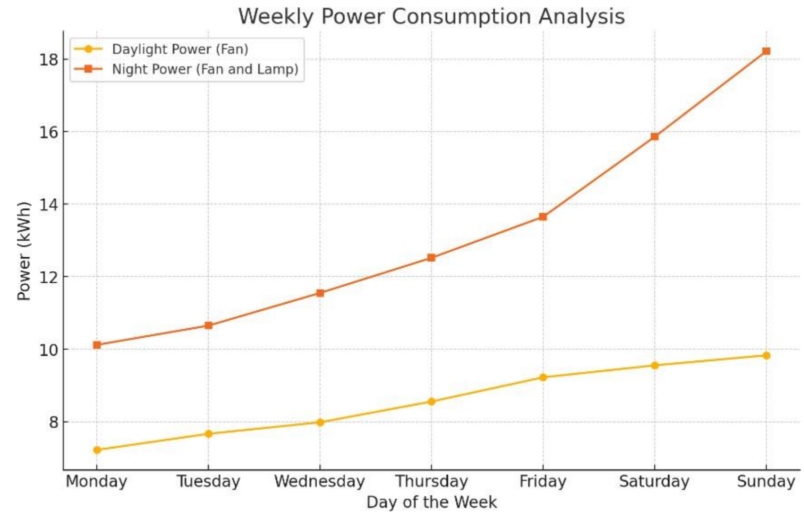

Figure 8: Weekly Power Consumption Analysis

Figure 8 provides a comprehensive analysis of weekly power consumption, differentiating between daylight power (fan only) and night power (fan and lamp) usage. Daylight power exhibits a relatively consistent trend, with a modest increase in energy consumption over the week. Starting at around 8 kWh on Monday, the consumption steadily rises to 10 kWh by Sunday. This suggests that fan usage during daylight hours remains relatively stable, with only a slight increment as the week progresses. In contrast, night power demonstrates a significantly steeper increase throughout the week. Beginning at approximately 12 kWh on Monday, it escalates rapidly, reaching around 18 kWh by Sunday. This sharp rise in night power consumption is indicative of the combined energy demand from the fan and lamp, which is notably higher than fan usage alone. The growing difference between day and night consumption towards the weekend, particularly from Friday to Sunday, suggests increased night-time activity or longer operational hours during the later part of the week. This analysis highlights a marked disparity in energy consumption patterns between day and night. The consistently higher night power consumption underscores the need for efficient energy management, especially during night hours when both fan and lighting are in use, to mitigate excessive energy usage.

Web Data Analysis: Figure 9 to 11 present the voltage, total cost, and current usage over time, derived from cloud data. These graphs demonstrate the system's ability to track and analyze energy usage in real-time, providing users with actionable insights to reduce consumption.

Figure 9: Data Analysis for Voltage (Vrms) vs Time

Figure 9 displays voltage fluctuations in a smart energy system over a 15-minute period. The voltage varies significantly, ranging from approximately 245 to 247 volts. A notable drop occurs around 11:20, where the voltage sharply decreases before recovering. This real-time voltage tracking allows for immediate detection of anomalies or issues in the power supply, which is crucial for maintaining electrical system stability and efficiency in smart grid applications.

Figure 10: Data Analysis for Total (RM) Versus Time

Figure 10 illustrates energy consumption cost over a brief period, with time displayed on the x-axis and the energy cost in RM (Malaysian Ringgit) on the y-axis. The time series data suggests a progressive and steady increase in energy cost, with a noticeable rise beginning around 11:25 AM on January 13, 2024. The timestamp provided at 11:17:13 GMT+0800 marks a cost of RM 0.04643. This trend likely indicates incremental energy usage, reflecting a possible peak in energy demand during this interval. Such patterns could be insightful for optimizing energy usage and forecasting future consumption spikes.

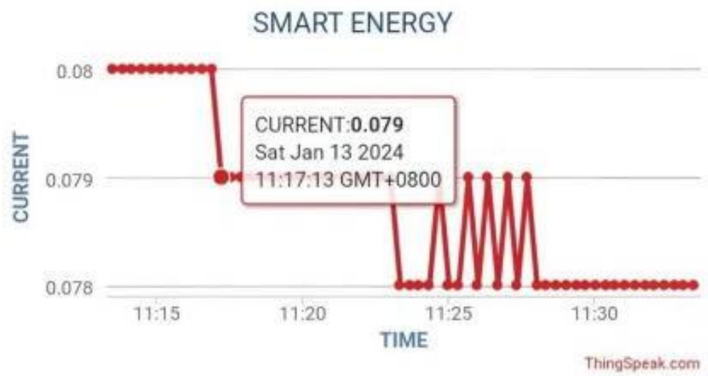

Figure 11: Data Analysis for Current versus Time

Figure 11 illustrates the fluctuations in current (measured in Amperes) over time, with a sharp drop observed around 11:15 AM on January 13, 2024. Initially, the current is stable at 0.08 A but then declines to approximately 0.079 A. Following this decline, a series of oscillations occurs between 0.078 and 0.079 A, suggesting intermittent variations in current flow until around 11:25 AM. This pattern may reflect electrical load changes or external factors affecting the current stability. Understanding these fluctuations is essential for assessing the efficiency of the energy system and determining potential areas for optimization or fault detection.

Conclusion and Future Work

This research successfully developed an IoT-based energy meter monitoring system that offers a cost-effective and efficient solution for managing energy consumption in smart homes. The system integrates hardware and software components, enabling real-time monitoring, control of appliances, and data analysis through a mobile application. The results demonstrated the system's ability to track energy consumption patterns, providing valuable insights into household electricity usage. This system is particularly beneficial for raising awareness of energy management, especially among student populations, and holds promise for wider applications in smart city initiatives.

For future work, several areas can be improved to enhance the system’s functionality. First, refining the hardware design and integrating more high-wattage appliances would yield more accurate readings and better energy management. Additionally, further research could focus on improving the precision of load and loss factor calculations. Extending compatibility to iOS platforms will also increase accessibility. Finally, exploring enhanced security measures for IoT-based energy meters and incorporating predictive analytics for energy usage forecasting would strengthen the system's robustness and adaptability in diverse residential and commercial environments. These advancements will further support energy conservation and efficient usage.

Acknowledgments

This work was supported in part by the Centre for Research and Innovation Management (CRIM), Fakulti Teknologi dan Kejuruteraan Elektronik dan Komputer (FTKEK) and Universiti Teknikal Malaysia Melaka (UTeM).

References

Anand, A., Chaudhary, Y., Mukherjee, R., & Yadav, A. (2021). GSM-based smart energy meter with theft detection and load control. In 2021 7th International Conference on Signal Processing and Communication (ICSC) (pp. 59–62).

Abdullah, R.S., Hakimi, H., & Kamalrudin, M. (2024). Software Security Readiness Index for Remote Working Employee in Public Organization: Preliminary Study. International Journal of Academic Research in Business and Social Sciences.

Avancini, D. B., Rodrigues, J., Rabêlo, R., Das, A., Kozlov, S., & Šolić, P. (2020). A new IoT- based smart energy meter for smart grids. International Journal of Energy Research, 45, 189–202.

Dass, D. V., Akhila, S., & Prasanjith, R. (2023). Smart energy meter using IoT. International Journal of Scientific Research in Science and Technology.

de Sousa, E. L., Marques, L., Felix de Lima, I. da S., Neves, A. B. M., Cunha, E. N., Kreutz, M., & Neto, A. (2023). Development of a low-cost wireless smart meter with power quality measurement for smart grid applications. Sensors, 23, 7210.

Enugurti, E., Ambekar, S., Dethe, R., & Sadu, M. (2023). Smart energy meter using IoT. International Journal of Advanced Research in Science, Communication and Technology.

Estibeiro, C. R. (2022). IoT-based energy meter reading system. International Journal of Advanced Research in Science, Communication and Technology.

Govindarajan, R., Meikandasivam, S., & Vijayakumar, D. (2020). Performance analysis of smart energy monitoring systems in real-time. Engineering, Technology & Applied Science Research, 10, 5808–5813.

Govindarajan, R., Meikandasivam, S., Malathi, R., & Kiranmai, M. (2020). Smart energy metering system using Android mobile application. International Journal for Research in Engineering Application & Management (IJREAM).

Hakimi, H., Kamalrudin, M., & Abdullah, R. S. (2023). Software Security Readiness Model For Remote Working In Malaysian Public Sectors: Conceptual Framework. Journal Of Theoretical And Applied Information Technology, 101(8).

Islam, M. H., Talukder, T. I., Saima, F. T. Z., Rimon, M. N. I., & Ali, J. (2021). An IoT-based smart energy meter with real-time power tracking system: A review. In 2021 6th International Conference on Smart and Sustainable Technologies (SpliTech) (pp. 01–05).

Jambi, J. R. A., Wong, W., Juwono, F., & Motalebi, F. (2023). Smart energy meter implementation: Security challenges and opportunities. In 2023 International Conference on Digital Applications, Transformation & Economy (ICDATE) (pp. 1–7).

Jha, A. S., Agrawal, A., & Rizwan, M. (2020). Smart energy meter and data logger. International Journal of Recent Technology and Engineering.

Jha, J. S., Pal, T. R., Sonawane, A. K., & Bhatia, S. (2023). Automated energy meter. International Journal of Scientific Research Updates.

Karthick, T., Raja, S. C., Nesamalar, J. D., & Chandrasekaran, K. (2021). Design of IoT-based smart compact energy meter for monitoring and controlling the usage of energy and power quality issues. Sustainable Energy, Grids and Networks, 26, 100454.

Kshirsagar, S., & Kshirsagar, S. (2021). IoT-based smart energy meter. SSRN Electronic Journal.

Rajeshbabu, Y., Mounika, E., Varalakshmi, J., Reddy, N. L., & Kumar, T. N. (2023). Smart energy meter using IoT. International Journal of Engineering Technology and Management Sciences, 7(3).

Selvan, S., Sivabalan, T., Ramesh, R., & Ragadeepa, H. (2023). IoT-enabled smart energy meter for energy management. In 2023 International Conference on Advances in Power, Signal, and Information Technology (APSIT) (pp. 280–284).

Sharma, C. J., Bhajbhuje, A. S., Tajane, N. R., & Dharmik, B. V. (2022). Design and implementation of smart energy meter. International Journal for Research in Applied Science and Engineering Technology.

Sheeba, R., Naufal, N. N., Beevi, S. N., Nair, A. R., Amal, S., Kumar, A. S., Mohan, A., Arunjith, P. M., Aswin, U., Aswanth, T., Joseph, J., & Jose, J. (2021). Real-time monitoring of energy meters using cloud storage. In 2021 IEEE International Power and Renewable Energy Conference (IPRECON) (pp. 1–5).

Subhash, R., Balaji, V., Sanjana, K., Madhavan, N., & Siva, T. (2020). Smart automated energy meter. In Emerging Technology Trends in Electronics, Communication and Networking (pp. 19–28).

Tahir, S. J., Bihani, P., & Tiwari, P. (2022). Energy metering and controlling using Android and IoT-based smart system. In 2022 Third International Conference on Intelligent Computing Instrumentation and Control Technologies (ICICICT) (pp. 931–936).