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Analysis of the Effect of an IoT Monitoring System on the Rate of Voltage Decline in 18650 Li-Ion Batteries Using Deep-Sleep and Non-Deep-Sleep Strategies

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Abstract

IoT-based monitoring systems often rely on batteries as their main power source; however, continuous data acquisition and transmission can accelerate battery voltage drop, thereby reducing operational lifespan. This research analyzes the effect of an Internet of Things (IoT)-based monitoring system on the voltage drop rate of 18650 Li-ion batteries, and compares the characteristics of voltage drop in deep-sleep and non-deep-sleep operating modes using a comparative quantitative experimental approach. The ESP32-based monitoring system was tested under three operating conditions: baseline (without a monitoring system), deep-sleep, and non-deep-sleep. Battery voltage measurements were carried out periodically over a predetermined observation duration. The results show that the IoT monitoring system affects the characteristics of battery voltage drop, and that different device operating modes result in different voltage drop rates. The non-deep-sleep condition exhibits the fastest voltage drop, while the deep-sleep strategy is able to reduce the rate of voltage drop more effectively than continuous operation. These findings indicate that the deep-sleep strategy contributes to improved energy efficiency in battery-based monitoring systems and may represent a more appropriate approach to slowing the rate of battery discharge, supporting the development of more energy-efficient and reliable IoT systems.

INTRODUCTION

Internet of Things (IoT)-based monitoring systems operate through a process of data acquisition by sensors, initial processing on microcontrollers, and the transmission of data to servers or cloud platforms for storage and visualization. In a battery monitoring system, the device periodically reads battery voltage and supporting parameters, processes the measurement results, and then sends them over a wireless network (Geetha et al., 2024; Zhang, 2023). This working pattern causes IoT nodes to function not only as measuring tools, but also as computing and communication units that are repeatedly active during system operation, such that the monitoring system has energy requirements that continuously arise throughout the processes of reading, processing, and transmitting data (Chen et al., 2024).

This issue becomes particularly significant when IoT nodes rely on batteries as their main power source. In this condition, the power consumption of the device directly affects the duration of system operation and the energy endurance of the battery. The more frequently the device is active to read sensors and transmit data, the more energy it consumes. Therefore, in a battery-based monitoring system, power consumption must be understood as a factor that determines the continuity of overall system operation (Mota et al., 2025).

One of the batteries widely used in portable devices and IoT nodes is the 18650 Li-ion battery. These batteries are favored due to their high energy density, compact size, and rechargeable nature, making them suitable for self-contained monitoring applications. The performance of the 18650 Li-ion battery is best understood through its discharge characteristics. As long as the battery is supplying a load, the voltage will gradually decrease according to the current drawn, the duration of operation, and the thermal conditions of the battery, such that the rate of voltage drop can serve as a practical indicator for assessing the energy performance of the battery during system operation (Sarabia-Jácome et al., 2025).

In IoT monitoring systems, the relationship between device load and battery voltage drop becomes increasingly evident when associated with the microcontroller's operating mode. In non-deep-sleep mode, the device tends to remain continuously active with relatively high power consumption, causing the battery to supply current throughout the entire operating period. In contrast, in deep-sleep mode, the device is only active during measurement and data transmission, then enters a power-saving state during the waiting interval. This difference in working patterns results in different average power consumption levels, and consequently different rates of battery voltage decline (Fathurahman, 2024).

A number of previous studies have shown that power management strategies play an important role in improving the energy efficiency of battery-based IoT nodes. However, studies on the energy efficiency of IoT nodes and those on battery performance are still often discussed separately (Saputra et al., 2025). Based on these conditions, there remains a gap in studies that directly compare the effect of deep-sleep and non-deep-sleep modes on the rate of voltage drop of 18650 Li-ion batteries using baseline conditions as a natural point of comparison. Therefore, this study was conducted to analyze the influence of an IoT-based monitoring system on the voltage drop rate of the 18650 Li-ion battery, compare the voltage drop characteristics across the two operating modes, and examine the application of the deep-sleep strategy as a means of mitigating system power consumption to reduce the rate of battery voltage decline (Kocsis Szürke et al., 2025).

The Internet of Things (IoT) is a concept that connects physical devices, sensors, computing systems, and communication networks to automatically acquire and exchange data. In a monitoring system, IoT enables data from observed objects to be collected, transmitted, and displayed continuously, allowing monitoring to be carried out remotely and more efficiently (Choudhary et al., 2024). IoT architecture is generally described through three main layers: the perception layer, the network layer, and the application layer. In this study, battery voltage readings were carried out at the perception layer, data transmission via Wi-Fi operated at the network layer, and ThingSpeak served as the application layer (Krishna et al., 2024). Beyond being a data acquisition and delivery system, IoT also has implications for device power consumption, as the activities of reading, local processing, and transmitting data to online platforms all require energy, making the system operation pattern an important factor in the energy efficiency of battery-based devices (Hammoud et al., 2025).

An IoT-based battery voltage monitoring system is a system that enables battery voltage conditions to be observed automatically and remotely. Through this approach, data is not only read on the device, but also transmitted to an online platform for periodic storage and monitoring (Krishna et al., 2024). The general working process begins with reading the battery voltage, after which the data is processed by a microcontroller and then transmitted through the communication network to the storage or data display medium. In this study, a monitoring system was used to read the voltage of the 18650 Li-ion battery, process the data via ESP32, and send it to ThingSpeak. Since the processes of reading, processing, and transmitting data all require energy, the presence of a monitoring system can also affect the observed energy performance of the battery (Christakis et al., 2024; Gozuoglu et al., 2025).

The 18650 Li-ion battery is one type widely used in portable devices and battery-based electronic systems due to its high energy density, compact size, and relatively stable performance. In this study, the 18650 Li-ion battery was selected as the test object because of its suitability for independently operated monitoring systems (Casado et al., 2025). The test object used is a Samsung 35E battery with specifications as shown in Table 1. The use of batteries of the same type and specification across all test scenarios aims to maintain consistency in the basic characteristics of the battery, so that differences in observed results can be more readily attributed to the treatment applied through the operating mode of the monitoring system (Czerniak et al., 2025; Wheeler et al., 2025).

Discharge is the process by which a battery releases energy to supply a load. During this process, battery voltage gradually decreases as stored energy diminishes. In Li-ion batteries, the voltage drop pattern is generally non-linear, but tends to be relatively stable at the beginning of use before declining more rapidly as the battery approaches its lower voltage limit (Armenta-Deu, 2025). In this study, voltage drop is used as an indicator of battery energy performance during the operation of the IoT monitoring system. The greater the effective load the battery receives, the faster the voltage decreases over time; therefore, discharge characteristics form the basis for explaining the differences in voltage drop rates across the baseline, deep-sleep, and non-deep-sleep conditions (Abbasi et al., 2025; Nguyen et al., 2025).

ESP32 is a microcontroller widely used in IoT systems due to its built-in Wi-Fi connectivity and data processing capabilities in a single device. In the monitoring system, ESP32 is responsible for reading data, processing measurement results, and transmitting them to online platforms, making its power consumption one of the important factors in determining the energy efficiency of battery-based systems (Espressif Systems, 2025). The difference in ESP32's energy requirements is influenced by the operating mode used. In the active state, the device performs full data reading, processing, and communication, resulting in relatively high power demands. In contrast, in deep-sleep mode, only certain minimum functions remain active, allowing power consumption to be significantly reduced (Espressif Systems, 2025; Sarabia-Jácome et al., 2025). A general comparison of ESP32 operating modes is presented in Table 2.

The operating mode of a microcontroller determines how the device uses energy during system operation. In non-deep-sleep conditions, the device remains continuously active so that data reading, processing, and communication can take place without interruption. In contrast, in deep-sleep mode, most primary functions are temporarily shut down and the device only reactivates at predetermined intervals according to system settings (Espressif Systems, 2025). In a battery-based monitoring system, the difference between the two modes affects the average power consumption of the device. Non-deep-sleep tends to result in higher energy consumption because the device is always in an active state, whereas deep-sleep enables energy savings as device uptime is shortened (Sarabia-Jácome et al., 2025; Pires et al., 2025). A general comparison of the two operating modes is presented in Table 3.

Research on IoT-based battery monitoring systems generally focuses on the device's ability to read, transmit, and display battery parameters in real time. Krishna et al. (2024) developed an IoT and LoRa-based battery management system to monitor voltage, current, temperature, state of charge, and state of health, though the primary focus remains on monitoring system integration and communication performance. Rao et al. (2024) designed an IoT-based lithium-ion cell monitoring system for real-time observation of battery parameters, with an orientation toward monitoring functions and successful data acquisition.

Research on the energy efficiency of IoT devices shows that power consumption is greatly influenced by node operation patterns. Bhavya and Harikrishnan (2025) demonstrated that hardware optimization and voltage scaling in battery-based IoT devices can reduce power consumption. Supriyanto and Anggono (2025) showed that the power consumption of the

ESP32 differs significantly according to the operating pattern and workload of the monitoring system. Sarabia-Jácome et al. (2025) explain that ESP32-based low-power sensor nodes utilize deep-sleep capabilities to regulate power status and suppress energy consumption. However, these studies have not directly analyzed the rate of battery voltage decline resulting from different operating modes. The novelty of this study lies in the comparative analysis of the influence of deep-sleep and non-deep-sleep modes on the rate of battery voltage decline in IoT monitoring systems, accompanied by baseline conditions as a natural point of comparison (Brito et al., 2025).

Therefore, this study was conducted to analyze the influence of an IoT-based monitoring system on the voltage drop rate of 18650 Li-ion batteries, to compare the voltage drop characteristics between deep-sleep and non-deep-sleep operating modes, and to examine the effectiveness of the deep-sleep strategy in mitigating system power consumption and reducing the rate of battery voltage decline. This research is expected to provide both theoretical and practical benefits. Theoretically, this study enriches understanding of the relationship between IoT node operating modes and lithium-ion battery discharge characteristics, and provides an empirical basis for the development of energy consumption models in battery-based IoT monitoring systems. Practically, this research offers recommendations for IoT system designers in selecting appropriate operating modes (deep-sleep versus non-deep-sleep) according to battery life requirements, supports the development of more energy-efficient and reliable IoT-based monitoring systems particularly in remote or off-grid applications, and serves as a reference for optimizing power management strategies to extend battery operational life without sacrificing monitoring functionality.

METHOD

Types and Approaches to Research

This study uses an experimental design with a comparative quantitative approach. The experimental design was chosen because the study was directed to test the effect of certain treatments on the change of the bound variable in a measurable manner, namely the effect of deep-sleep and non-deep-sleep operation strategies on the rate of voltage drop of 18650 Li-ion batteries (Kotronoulas et al., 2023; Watson & Torgerson, 2023). The quantitative approach is used because the data generated in the form of measurement results, such as battery voltage values, observation time intervals, and voltage change rates, are objectively analyzed to compare battery responses under three test conditions (Maier et al., 2023; Australian Journal of Management, 2024).

Research Location and Time

The research was carried out at home as the main location for designing, tool assembly, IoT monitoring system programming, functional testing, and data collection. The implementation of the research began in January with the literature study stage. In March, the design and assembly of the equipment and the implementation of the program were carried out. Furthermore, data collection was carried out in April in two stages, each for about two weeks, namely primary data collection and re-data collection for tool validation.

Designing a Monitoring System

The design of the monitoring system in this study was carried out to build an IoT-based system that is able to read battery voltage, record temperature, and send measurement data to online platforms periodically. This system is designed to support the data collection process in the testing of the Li-ion 18650 battery with two operating modes, namely deep-sleep and non-deep-sleep. The prototype monitoring system consists of the ESP32, a series of voltage readings, temperature sensors, and other supporting components.

Tool Components and Specifications

The components used in the study include the ESP32 microcontroller, voltage sensor via a voltage divider circuit, temperature sensor, Samsung 35E 18650 Li-ion battery, and the ThingSpeak IoT platform. The study used three test batteries of the same specification to ensure the consistency of the test. The deep-sleep mode is set with the active cycle every 10 minutes, while the non-deep-sleep mode runs continuously.

Testing Scenarios and Procedures

Tests were performed on three scenarios to distinguish the natural voltage drop of the battery from the voltage drop affected by the load monitoring system. Baseline conditions are used as a natural benchmark when the battery is not overloaded by the monitoring device. Deep-sleep and non-deep-sleep conditions were used to see the effect of differences in device operating patterns on voltage drop characteristics. The initial voltage of the entire battery is uniform at 4.25 V, while the test end limit is set at 2.3 V.

Data Analysis Methods

Data analysis is carried out through several stages. First, pre-processing of data to ensure the quality and completeness of the data. Second, the calculation of voltage drop and voltage drop rate based on voltage change over time. Third, verify the results of the system's measurement against the multimeter. Fourth, trend and comparative analysis between scenarios. Fifth, deep-sleep effectiveness analysis based on comparative results. Voltage data is obtained through a monitoring system and manually verified using a multimeter to ensure the reliability of the data before further analysis (DerakhshanFard et al., 2025; Mota et al., 2025).

RESULTS AND DISCUSSION

Testing Overview

The test in this study was carried out to analyze the influence of an IoT-based monitoring system on the voltage drop rate of 18650 Li-ion batteries. The focus of the test was directed at the comparison of the characteristics of battery voltage drop at three conditions, namely baseline, deep-sleep, and non-deep-sleep. The selection of the three conditions is based on the principle that IoT monitoring systems require energy to perform data reading, processing, and data transmission, so the device's mode of operation could potentially affect power consumption and battery response during testing (DerakhshanFard et al., 2025; Mota et al., 2025). A summary of the test scenarios is presented in Table 1.

Table 1. Summary of Research Testing Scenarios

Scenario	Test Conditions	Initial Voltage	Duration of Observation	Measurement Method
Battery A	Baseline without monitoring tools	4.25 V	7 days	Manual measurement using a multimeter
Battery B	IoT monitoring system with deep-sleep ON	4.25 V	12 days	Automated measurement via IoT system and multimeter verification
C Battery	IoT monitoring system with non-deep-sleep OFF	4.25 V	33 hours	Automated measurement via IoT system and multimeter verification

Source: Samsung SDI. (2020). *INR18650-35E Specification Sheet*. Data sheet No. SDIREA-201909-01

Results of the Initial Function Test of the Monitoring System

Before being used in the main test, the monitoring system first undergoes an initial functional test to ensure that all key components and features can work according to design.

Initial function testing was performed on several key parts of the system, including battery voltage readings, temperature readings, data transmission to IoT platforms, deep-sleep functions, non-deep-sleep functions, data timekeeping, and general system operation stability (Kamyod et al., 2025; Krishna et al., 2024). The results of the initial function test are presented in Table 5.

Table 2. Results of the Initial Function Test of the Monitoring System

No	Components/Functions Tested	Success Indicators	Test Results	Status
1	Battery voltage readings	Voltage values can be read and recorded	The battery voltage is successfully read and stored in the system	Successful
2	Temperature readings	Temperature values can be read and recorded	The temperature is successfully read and recorded on the system	Successful
3	Data delivery to IoT platforms	Data can be sent and received periodically	Voltage and temperature data successfully displayed on the platform	Successful
4	ESP32 deep-sleep function	The system can enter deep-sleep mode as per the program	Deep-sleep mode runs as per settings	Successful
5	Non-deep-sleep function	The system stays active without going into sleep mode	System runs continuously without sleep	Successful
6	Data timing	Data capture time is recorded correctly	Measurement timestamps are stored on each data	Successful
7	The Stability of the Monitoring System	The system remains working during the test	The system is able to work and record data during observation	Successful

Source: Espressif Systems. (2025). ESP32 Series Datasheet (Version 4.5), pp. 27–29

Based on Table 2, all the main functions of the monitoring system can run according to the success indicators that have been set. Thus, the testing stage can proceed to data capture in each scenario (Kamyod et al., 2025; Krishna et al., 2024).

Battery A Test Results (Baseline)

In the baseline scenario, battery A is tested without being connected to a monitoring system. This test aims to show the natural tendency of decreasing battery voltage without additional load from electronic devices, so the results are used as a basic reference. The data from the observation of battery voltage A is presented in Table 6.

Table 3. Battery Voltage Data A against Time in Baseline Scenarios

No	Observation Time	Battery Voltage (V)	Temperature (°C)	Remarks
1	30-03-2026 11:00	4,25	29,68	Initial voltage testing

2	31-03-2026 11:00	4,25	29,09	Day 1
3	01-04-2026 11:00	4,25	29,49	Day 2
4	02-04-2026 11:00	4,25	28,79	Day 3
5	03-04-2026 11:00	4,25	28,24	Day 4
6	04-04-2026 11:00	4,24	29,93	Day 5
7	05-04-2026 11:00	4,24	28,99	Day 6
8	06-04-2026 11:00	4,24	29,26	Day 7
9	07-04-2026 11:00	4,24	29,50	Day 8
10	08-04-2026 11:00	4,24	29,83	Day 9
11	09-04-2026 11:00	4,23	28,60	Day 10
12	10-04-2026 11:00	4,23	29,48	Day 11
13	11-04-2026 11:00	4,23	30,17	Day 12
14	12-04-2026 11:00	4,23	29,24	Test end voltage

Source: Compiled from Espressif Systems (2025) and Sarabia-Jácome et al. (2025)

Table 3 shows that the battery voltage A in the baseline scenario decreased very little during the observation period, from 4.25 V down to 4.23 V in 12 days. This indicates that in the absence of additional load from the monitoring system, the 18650 Li-ion battery tends to have high voltage stability during the test period.

Battery B (Deep-Sleep) Test Results

In the deep-sleep scenario, battery B is connected to an IoT monitoring system that is operated using a power-saving strategy. The monitoring device is only active at certain times to perform data readings and data transmission, then return to deep-sleep mode during the waiting interval. The data from the observation of battery B voltage is presented in Table 7.

Table 4. Battery Voltage Data B to Time in Deep-Sleep Scenarios

No	Observation Time	Battery Voltage (V)	Temperature (°C)	Remarks
1	30-03-2026 11:02:36	4,23585	29,6875	Initial observation
2	31-03-2026 10:57:36	4,06658	28,8125	Day 1

3	01-04-2026 11:02:45	4,09479	29,2500	Day 2
4	02-04-2026 10:57:48	4,09479	28,5625	Day 3
5	03-04-2026 11:04:53	3,99403	28,0625	Day 4
6	04-04-2026 10:59:34	3,99806	29,5625	Day 5
7	05-04-2026 11:04:18	3,97791	28,6875	Day 6
8	06-04-2026 11:01:49	3,69579	28,8750	Day 7
9	07-04-2026 10:56:53	3,67161	29,1250	Day 8
10	08-04-2026 11:03:27	3,59503	29,5625	Day 9
11	09-04-2026 10:57:48	3,48218	28,6250	Day 10
12	10-04-2026 11:04:31	3,35321	29,2500	Day 11
13	11-04-2026 11:00:48	3,23633	30,1250	Day 12
14	12-04-2026 09:16:12	2,80509	28,5000	End of observation

Source: Baseline measurement data, this study (2026)

Table 4 shows that battery B voltage decreased significantly compared to the baseline scenario, from 4.23585 V down to 2.80509 V in 12 days. This condition shows that the existence of a monitoring system still puts an additional load on the battery, even though the device is operated with a deep-sleep strategy. However, the voltage drop in this scenario still occurs gradually during the observation period, indicating that the deep-sleep mode is able to reduce the power consumption of the monitoring system so that the voltage drop does not occur too quickly.

C (Non-Deep-Sleep) Battery Test Results

In non-deep-sleep scenarios, the C battery is connected to an IoT monitoring system that is operated without a power-saving strategy, so that the monitoring device remains active continuously. The data from the observation of battery C voltage is presented in Table 8.

Table 5. Battery Voltage Data C against Time in Non-Deep-Sleep Scenarios

No	Observation Time	Battery Voltage (V)	Temperature (°C)	Remarks
1	30-03-2026 10:34:48	4,23988	29,6250	Initial observation
2	30-03-2026 12:33:47	4,08270	30,7500	Further observations
3	30-03-2026 14:33:47	3,89327	29,1250	Further observations

4	30-03-2026 16:33:47	4,07867	28,0625	Further observations
5	30-03-2026 18:33:48	4,01821	28,2500	Further observations
6	30-03-2026 20:33:48	3,95373	27,8125	Further observations
7	30-03-2026 22:33:48	3,85700	27,8750	Further observations
8	31-03-2026 00:33:48	3,82476	27,7500	Further observations
9	31-03-2026 02:33:47	3,68370	27,6875	Further observations
10	31-03-2026 04:33:47	3,67564	27,4375	Further observations
11	31-03-2026 06:33:47	3,59906	27,3750	Further observations
12	31-03-2026 08:33:47	3,51442	27,9375	Further observations
13	31-03-2026 10:33:50	3,39352	28,7500	Further observations
14	31-03-2026 12:33:47	3,33709	29,8750	Further observations
15	31-03-2026 14:33:47	3,19200	29,6875	Further observations
16	31-03-2026 16:33:47	2,99451	30,1875	Further observations
17	31-03-2026 18:33:47	2,92197	28,8750	Further observations
18	31-03-2026 20:26:47	2,35370	28,8125	End of observation

Source: Non-deep-sleep measurement data, this study (2026).

Table 5 shows that the voltage of the C battery decreases the fastest compared to the other two scenarios. In the observation time of only about 33 hours, the battery voltage has dropped from 4.23988 V to 2.35370 V. This shows that the monitoring system that continues to be active without a power-saving strategy puts a large load on the battery.

Comparative Analysis of Voltage Drop Between Scenarios

The test results showed that the voltage drop of the 18650 Li-ion battery was affected by the presence of an IoT-based monitoring system and the operating mode of the device used. Under baseline conditions, voltage drop occurs at the slowest because the battery is not overloaded by data reading, processing, and transmission activities. In contrast, in non-deep-sleep conditions, voltage drops occur most quickly because the microcontroller and communication module remain active during the test period. The deep-sleep condition showed a lower voltage drop rate than non-deep-sleep, but it was still higher than baseline (DerakhshanFard et al., 2025; Mota et al., 2025).

This difference is in line with the working principle of battery-based IoT nodes, where energy is used not only for measurement, but also for wireless computing and communication processes. In deep-sleep mode, the device is only active at certain intervals, then returns to a power-saving state, resulting in a shorter device uptime and the system's energy consumption can be suppressed (DerakhshanFard et al., 2025; Gerndt et al., 2025). When associated with the characteristics of the battery discharge, the results of this study show that the greater the effective load the battery receives, the faster the terminal voltage decreases, according to studies on the behavior of lithium-ion batteries (Koláček et al., 2025).

Verification and Validation of Test Results

Verification of measurement results is carried out to assess the suitability of voltage readings by the monitoring system to the reference measuring instrument, namely multimeters. This step is important because the research demands that the data produced have an adequate level of reliability to be analyzed (Koláček et al., 2025; Sukardi et al., 2025). The verification results are presented in Table 9.

Table 6. Validation Results of Monitoring System Testing on Multimeters

Day To	Measurement Time	System Voltage (V)	Voltage Multimeter (V)	Difference (V)
1	11.00	4,25585	4,25	0,00585
2	11.00	4,06658	4,07	0,00342
3	11.00	4,09479	4,09	0,00479
4	11.00	4,09479	4,09	0,00479
5	11.00	3,99403	3,99	0,00403
6	11.00	3,99806	4,00	0,00194
7	11.00	3,97791	3,98	0,00209
8	11.00	3,69579	3,70	0,00421
9	11.00	3,67161	3,67	0,00161
10	11.00	3,59503	3,60	0,00497
11	11.00	3,48218	3,48	0,00218
12	11.00	3,35321	3,35	0,00321
13	11.00	3,23633	3,24	0,00367
14	11.00	2,80509	2,81	0,00491

Source: Device verification data, this study (2026).

Table 6 shows that the difference in readings between the monitoring system and the multimeter is very small, ranging from 0.00161 V to 0.00585 V. The results of this verification show that the monitoring system is suitable for use as a data collection tool in the research. The reading difference that arises can be influenced by the resolution of the ADC on the ESP32, the tolerance of the resistor in the voltage divider circuit, and the possibility of noise interference during the reading process (Nkinyam et al., 2025; Rao et al., 2024).

Analysis of the Effectiveness of Deep-Sleep Strategies

Analysis of the effectiveness of the deep-sleep strategy shows that the power-saving operating mode is able to reduce the rate of battery voltage drop compared to non-deep-sleep conditions. Technically, this effectiveness can be explained by the deep-sleep method that limits the active duration of ESP32 only during the reading and data transmission process. Once the process is complete, the device returns to a power-saving state so that the average energy consumption of the system is lower than continuous operation. Studies on energy management in IoT devices show that sleep-wake scheduling and device uptime reduction are effective approaches to reduce the energy requirements of the system (DerakhshanFard et al., 2025; Mota et al., 2025).

When associated with the characteristics of the battery voltage drop, the decrease in power consumption in deep-sleep mode causes the battery to release energy more slowly than in non-deep-sleep mode. This is in accordance with studies of lithium-ion batteries which show that the difference in charge level will affect the speed of the terminal voltage drop during the discharge process (Koláček et al., 2025). Overall, the deep-sleep strategy can be considered a more effective operating approach than non-deep-sleep for battery-powered IoT-based monitoring systems. In applications that demand longer battery life, the use of deep-sleep is a more appropriate choice as it is able to mitigate system power consumption and slow down the rate of battery discharge without eliminating the main functions of the monitoring system (Mota et al., 2025; Gerndt et al., 2025).

CONCLUSION

This study proves that the IoT-based monitoring system has an effect on the voltage drop characteristics of the 18650 Li-ion battery, where in the baseline condition the battery shows the smallest voltage drop rate because it is not burdened by data acquisition and transmission activities; in non-deep-sleep conditions the voltage drop rate becomes the highest due to continuous active devices; and in deep-sleep conditions The rate of voltage drop is lower because the device is only active at certain intervals, so the deep-sleep strategy has proven to be effective as a power consumption mitigation effort that is able to slow down the rate of battery discharge. For further research, it is recommended to add other observation parameters besides voltage, such as current, temperature, capacity, or estimated state of charge, use a variety of battery types to evaluate the consistency of results, test on more controlled environmental conditions, and optimize the duty cycle and power management algorithms to ensure that IoT-based monitoring systems have longer battery life and more reliable performance in practical implementation.

REFERENCE

Abbasi, A. M., et al. (2025). *Real-time discharge curve and state of charge estimation for lithium-ion batteries via physics-informed neural networks*.

Armenta-Deu, C. (2025). Online determination of state of charge in lithium-ion batteries. *Frontiers in Energy Research*, *13*. https://doi.org/10.3389/fenrg.2025.1573972

Australian Journal of Management. (2024). What is quantitative research? An overview and guidelines. *Australian Journal of Management*.

Bhavya, A. R., & Harikrishnan, S. (2025). Optimizing energy efficiency in battery-powered IoT devices through hardware optimization and voltage scaling. *Engineering, Technology & Applied Science Research*.

Brito, S. D., Azinheira, G. J., Semião, J. F., Sousa, N. M., & Litrán, S. P. (2025). Non-intrusive low-cost IoT-based hardware systems for sustainable predictive maintenance of industrial pump systems. *Electronics*.

Casado, P., et al. (2025). Evaluation of commercial Li-Ion 18650 battery cells for demanding applications. *Journal of Power Sources*.

Chen, K., Luo, L., Lei, W., Lv, P., & Zhang, L. (2024). Design and implementation of online battery monitoring and management system based on the Internet of Things. *Frontiers in Energy Research*, *12*. https://doi.org/10.3389/fenrg.2024.1454398

Choudhary, A., Tiwari, A., Sharma, A., & Singh, P. (2024). Internet of Things: A comprehensive overview, architectures, applications, simulation tools, challenges, and future directions. *Discover Internet of Things*. https://doi.org/10.1007/s43926-024-00084-3

Christakis, I., Orfanos, V. A., Chalkiadakis, P., & Rimpas, D. (2024). Real-time monitoring of a lithium-ion battery module to assess operational status and thermal field. *Engineering Proceedings*, *82*(1).

Czerniak, J., Gacek, & Ziembik. (2025). *Experimental evaluation and analysis of 18650 lithium-ion batteries*.

DerakhshanFard, N., Rajabi Bavil Olyaei, A., & RashidJafari, F. (2025). Optimization of energy management in IoT devices using LSTM models: Energy consumption prediction with sleep-wake scheduling control. *Intelligent Systems with Applications*, *25*. https://doi.org/10.1016/j.iswa.2025.200624

Espressif Systems. (2025a). *ESP32 series datasheet* (Version 4.5).

Espressif Systems. (2025b). *ESP32 SoC series*.

Fathurahman, M. (2024). Implementation of deep sleep mode in LoRa-based cigarette smoke detection systems in Islamic boarding schools. *SPEKTRAL: Journal of Communications, Antennas and Propagation*.

Geetha, A., Suprakash, S., & Lim, S.-J. (2024). Sensor based battery management system in electric vehicle using IoT with optimized routing. *Mobile Networks and Applications*, *29*(2), 349–372.

Gerndt, M., Sim, S. J. R., et al. (2025). Energy-aware duty cycle management for solar-powered IoT systems. *Sensors*, *25*(14), 4500.

Gozuoglu, A., Koksal, S., et al. (2025). *IoT-enhanced battery management system for real-time monitoring*.

Hammoud, H., Weis, F., Leclerc, M., & Bonnin, J.-M. (2025). Toward a more realistic energy consumption model for IoT nodes in extreme-edge computing environments. *IoTBDS 2025 Proceedings*. https://doi.org/10.5220/0013273800003944

Kamyod, C., et al. (2025). IoT-based system for real-time monitoring and AI-driven energy-aware operation. *Sensors*, *25*(24).

Kocsis Szürke, S., Kovács, G., et al. (2025). Analysis of the relationship between discharge cutoff voltage, usable capacity, and thermal behavior in cylindrical lithium-ion cells. *Applied Sciences*, *16*(1), 79. https://doi.org/10.3390/app16010079

Koláček, J., et al. (2025). Perspective modelling and measuring discharge voltage curves as tool for online state-of-charge diagnostics. *Applied Energy*.

Krishna, G., Salkuti, S. R., & Bansal, R. C. (2024). IoT-based real-time analysis of battery management system using customized LoRa-enabled device. *Results in Engineering*.

Maier, C., Laumer, S., Eckhardt, A., & Weitzel, T. (2023). Cross-sectional research: A critical perspective, use cases, and recommendations. *International Journal of Information Management*, *70*.

Mota, A., Serôdio, C., Briga-Sá, A., & Valente, A. (2025). Implementation of an Internet of Things architecture to monitor indoor air quality and estimate remaining battery time of sensor nodes. *Sensors*, *25*(6), 1683. https://doi.org/10.3390/s25061683

Nguyen, N., et al. (2025). Lithium-ion battery open-circuit voltage analysis for temperature compensation. *Energies*.

Nkinyam, C. M., et al. (2025). Development of a low-cost monitoring device for solar photovoltaics systems in developing countries. *Results in Engineering*.

Pires, L. M., et al. (2025). Design and development of a low-power IoT system for temperature monitoring in transport tracking applications. *Journal of Sensor and Actuator Networks*, *9*(3).

Rao, S. K., N. T., Rashmi, B. J. S., & Alladwar, S. (2024). Real time monitoring system for lithium-ion cell using IoT. In *Proceedings of the 2nd International Conference on Intelligent and Sustainable Power and Energy Systems (ISPES)* (pp. 119–123). https://doi.org/10.5220/0013579500004639

Saputra, R. H., et al. (2025). IoT-based application design for battery discharge monitoring based on variation in C-rate and temperature of lithium-ion battery. *ELKHA: Journal of Electrical Engineering*.

Sarabia-Jácome, D., Grasa, E., & Catalán, M. (2025). RINAsense: An open-source, low-power IoT sensor node for Recursive InterNetwork Architecture experimentation. *HardwareX*, *24*, e00719. https://doi.org/10.1016/j.ohx.2025.e00719

Sukardi, S., et al. (2025). Calibration and validation of IoT-based DC power logger. *Journal of Electronics, Automotive, and Technology*.

Supriyanto, S., & Anggono, S. U. (2025). Comparative analysis of power consumption and real-time performance between ESP32 and Raspberry Pi Pico W in IoT-based temperature monitoring systems. *Journal of Information and Communication Technology*.

Watson, R., & Torgerson, H. (2023). Increasing the use of experimental methods in nursing and midwifery education research. *Nurse Education in Practice*, *73*.

Wheeler, W., et al. (2025). An ageing study of twenty 18650 lithium-ion Graphite/LFP cells. *Scientific Data*.

Zhang, Q. (2023). Design of wireless battery management system monitoring and automated alarm system based on improved long short-term memory neural network. *PeerJ Computer Science*, *9*, e1345.