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Module-level power consumption analysis of ESP32 wroom and ESP32 dfrobot under normal and deep sleep operation

Achmad Zuchriadi[1*)], Sargi Ginting[2], Silvia Angraeni[3], Didit Widiyanto[4],
[1,2,3]Fakultas Teknik, Universitas Pembangunan Nasional Veteran Jakarta, Indonesia
[4]Fakultas Ilmu Komputer, Universitas Pembangunan Nasional Veteran Jakarta, Indonesia

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ABSTRACT

Energy efficiency is a critical requirement for battery-powered Internet of Things (IoT) systems, particularly those operating under duty-cycled conditions. Among widely adopted microcontroller platforms, ESP32 modules are extensively used due to their integrated connectivity and low-power features. In practice, ESP32 WROOM is commonly deployed because of its affordability and availability, while alternative modules such as ESP32 DFRobot are claimed to offer superior low-power performance. However, quantitative experimental comparisons at the module level remain limited. This study presents a controlled experimental evaluation of power consumption characteristics of ESP32 WROOM and ESP32 DFRobot modules operating in normal mode and deep sleep mode under realistic agricultural IoT workloads. Both modules were integrated with multiple environmental and soil sensors and LoRa communication, using identical hardware configurations, firmware logic, and measurement procedures. Power consumption was measured using a dual digital multimeter setup, with each operating condition evaluated over 50 repeated trials. The results show that both modules exhibit comparable power consumption during normal mode operation. In contrast, significant differences emerge during deep sleep mode. ESP32 WROOM consumes 36.907 mW in deep sleep, while ESP32 DFRobot consumes only 0.317 mW. Quantitative analysis indicates that ESP32 DFRobot achieves a deep sleep power efficiency improvement of approximately 99.14% relative to ESP32 WROOM. These findings demonstrate that module-level hardware design plays a decisive role in ultra-low-power performance and provide empirical guidance for selecting ESP32 modules in duty-cycled IoT deployments with significant implications for battery lifetime.

Corresponding Author:

Achmad Zuchriadi
Fakultas Teknik
Universitas Pembangunan Nasional Veteran Jakarta
Jalan RS. Fatmawati Raya, Pondok Labu, Cilandak, Jakarta, Indonesia 12450
Emil: achmad.zp@upnvj.ac.id

1. INTRODUCTION

The rapid growth of Internet of Things (IoT) applications has intensified the demand for energy-efficient embedded systems (Albreem et al., 2021; Han et al., 2022; Moloudian et al., 2024), particularly for deployments operating under limited power sources such as batteries or energy harvesting units (Lu et al., 2021; Sanislav et al., 2021; Sherazi et al., 2022). In many IoT scenarios, devices are required to operate autonomously for extended periods, making power consumption a critical factor that directly affects system lifetime, maintenance frequency, and overall deployment cost (Yüksel, 2020).

The ESP32 microcontroller family has emerged as one of the most widely adopted platforms for IoT systems due to its integrated Wi-Fi and Bluetooth connectivity, dual-core processing capability, and support for multiple power-saving modes (Alexander et al., 2017a, 2017b; Carlo et al., 2019; Plauska et al., 2023). Among these features, deep sleep mode plays a central role in reducing energy consumption by disabling the main CPU and most peripherals during idle periods, while maintaining minimal system functionality (Abdelmoneim et al., 2023a; Hadi & Ali, 2025). In practical IoT deployments, devices typically alternate between active (normal) operation and deep sleep mode following a duty-cycled pattern.

In Indonesia, ESP32 WROOM modules are particularly prevalent in IoT development and deployment(Adrian & Harmadi, 2024; Suherman et al., 2025) . This widespread adoption is largely driven by their relatively low cost, broad availability in local markets, and extensive community support. As a result, ESP32 WROOM is frequently selected as the default hardware platform in academic projects, prototyping activities, and small-scale industrial applications. However, the dominance of ESP32 WROOM in practice often leads to limited consideration of alternative ESP32 module variants (Indriyani et al., 2024; Kurniasari et al., 2025; Widiaratih et al., 2023).

One such alternative is the ESP32 DFRobot module, which, although less commonly used in Indonesia due to higher cost and more limited availability, is designed with a stronger emphasis on low-power operation (Kadir et al., 2021). According to manufacturer datasheets, the ESP32 DFRobot module integrates hardware features intended to reduce power consumption, particularly in low-power modes such as deep sleep. Despite these claimed advantages, empirical evidence comparing the real-world power efficiency of ESP32 DFRobot against the more commonly used ESP32 WROOM under identical operating conditions remains limited.

Previous studies on ESP32 power consumption have primarily focused on evaluating low-power modes at the microcontroller level or within a single module variant (Alexander et al., 2017b; Kareem & Dunaev, 2021; Umar Anggono, 2025). Consequently, there is a lack of systematic, measurement-based comparisons that assess how module-level hardware design influences power consumption in both normal and deep sleep modes. This gap is particularly relevant in contexts such as Indonesia, where hardware selection is often driven by cost and availability rather than experimentally validated energy efficiency.

Therefore, the research gap addressed in this study lies in the absence of controlled experimental comparisons between commonly used and alternative ESP32 modules—specifically ESP32 WROOM and ESP32 DFRobot—under identical normal and deep sleep operating conditions. Understanding whether the higher-cost ESP32 DFRobot module delivers tangible power efficiency benefits over the widely used ESP32 WROOM is essential for informed hardware selection in energy-constrained IoT systems.

This study adopts an agricultural IoT workload integrating multisensor data acquisition and LoRa communication to represent realistic duty-cycled operation. Rather than isolating the ESP32 core under minimal conditions, the proposed approach evaluates complete IoT node behavior, which more accurately reflects practical deployments. The main novelty of this work lies in a controlled, module-level comparison between ESP32 WROOM and ESP32 DFRobot using identical hardware, firmware, and workloads. This enables direct quantification of deep sleep power efficiency differences attributable to module-level hardware design.

2. RESEARCH METHOD

2.1 Research Design

This study employed a quantitative experimental research design to evaluate and compare the power consumption characteristics of two ESP32 module variants, namely ESP32 WROOM and ESP32 DFRobot, with the specific objective of identifying the more power-efficient module and quantifying the efficiency difference under normal mode and deep sleep mode operation.

An agricultural IoT monitoring system is incorporated as an experimental scenario to emulate duty-cycled operation commonly found in low-power IoT applications (Abdelmoneim et al., 2023b; Khan et al., 2022; Morchid et al., 2024; Pereira et al., 2023) . The application context serves as a representative workload and does not limit the general applicability of the experimental methodology.

2.2 ESP32 Module Selection

Two commercially available ESP32 modules were selected for evaluation: (a) ESP32 WROOM, which is widely adopted in Indonesia due to its lower cost, broad availability, and extensive community support. (b) ESP32 DFRobot, which is designed with a stronger emphasis on low-power operation, particularly during deep sleep mode. Although both modules are based on the same ESP32 chipset, differences in onboard voltage regulation, power distribution, and auxiliary circuitry may influence real-world power consumption, especially in low-power operating states.

2.3 Hardware Configuration

Each ESP32 module was tested independently using an identical hardware configuration to ensure a fair comparison. Power was supplied using a regulated DC source set to a constant voltage in accordance with the recommended operating specifications of the modules. The onboard power regulation circuitry of each module was utilized without modification to reflect typical deployment conditions.

All experiments were conducted in a controlled laboratory environment at room temperature. Prior to data acquisition, the system was allowed to reach steady-state conditions to minimize transient effects associated with power-up and operating mode transitions.

2.4 Firmware Configuration and Operating Modes

Identical firmware logic was deployed on both ESP32 modules using the same development environment, compiler settings, and clock configuration. Wireless communication was implemented using LoRa technology, while Wi-Fi and Bluetooth interfaces were disabled to prevent additional variability in power consumption.

Two operating modes were evaluated (a) Normal Mode - the ESP32 operated in an active state, performing multi-sensor data acquisition and transmitting the collected data via the LoRa module, (b) Deep Sleep Mode - after completing sensing and transmission tasks, the ESP32 entered deep sleep mode using a timer-based wake-up mechanism. In this state, the main CPU and most peripheral subsystems were powered down, leaving only the ultra-low-power domain active.

During deep sleep, all external sensors and the LoRa transceiver are placed in hardware sleep or powered-off states, with sensing and communication disabled. This configuration ensures experimental fairness by isolating module-level deep sleep power consumption, allowing observed differences to be attributed primarily to ESP32 module hardware rather than peripheral activity.

2.5 Agricultural IoT System and Sensor Data Acquisition

To approximate realistic agricultural field conditions, each ESP32 module was configured as an agricultural monitoring node integrating multiple environmental and soil sensors, consisting of: (a) Rain Sensor, to detect rainy or clear weather conditions; (b) DS18B20, to measure soil temperature; (c) pH Sensor, to measure soil acidity; (d) Soil Moisture Sensor, to measure soil moisture content; (e) BMP280, to measure ambient air temperature, atmospheric pressure, and altitude.

During each operational cycle, the ESP32 acquired data from all connected sensors, performed minimal processing, and transmitted the sensor data via the LoRa transceiver. Following data transmission, the system transitioned into deep sleep mode for a predefined interval. The same sensing sequence, data packet structure, transmission interval, and sleep duration were applied to both ESP32 modules to ensure experimental consistency.

2.6 Power Measurement Setup

Power consumption measurements were conducted using two digital multimeters to independently measure voltage and current: (a) One digital multimeter was connected in parallel with the power supply terminals to continuously measure the supply voltage. (b) A second digital multimeter was connected in series with the power supply line to measure the current drawn by the ESP32 system, including sensors and the LoRa module. This dual-instrument configuration enables accurate power calculation by reducing measurement uncertainty, particularly during low-current deep sleep operation. Measurements were recorded only after the system reached steady-state conditions in each operating mode.

2.7 Experimental Parameters and Test Conditions

To ensure consistency, repeatability, and fair comparison between the two ESP32 module variants, all experiments were conducted using identical system configurations, operating conditions, and measurement procedures. The key experimental parameters applied throughout this study are summarized in Table 1.

Table 1. Experimental Parameters and Test Conditions

Parameter	Specification / Setting	Remarks
ESP32 modules	ESP32 WROOM, ESP32 DFRobot	Module-level comparison
Application scenario	Agricultural IoT monitoring	Multi-sensor workload
Sensors	Rain, DS18B20, pH, Soil Moisture, BMP280	Identical configuration
Communication	LoRa transceiver	Same frequency and TX power
Power supply	Regulated DC source	Constant voltage
Voltage measurement	Digital multimeter (parallel)	Independent voltage reading
Current measurement	Digital multimeter (series)	Independent current reading
Operating modes	Normal mode, Deep sleep mode	Evaluated separately
Firmware logic	Identical	Same code and parameters
Duty cycle	Fixed	Timer-based wake-up
Number of measurements	50 per mode per module	Statistical reliability
Measurement condition	Steady-state	After stabilization
Environment	Laboratory, room temperature	Controlled conditions

2.8 Data Collection and Analysis

For each ESP32 module, 50 measurement trials were conducted in normal mode and 50 trials in deep sleep mode, resulting in 100 measurement samples per module. Average values and standard deviations were calculated to characterize power consumption behavior and variability.

Power consumption was calculated using the measured voltage and current values. Comparative analysis was performed to identify differences attributable to module-level hardware design, rather than firmware behavior or application logic.

In addition to direct power consumption comparison, a relative power efficiency metric was calculated based on deep sleep power values to quantify the efficiency difference between the two ESP32 modules

2.9 Experimental Setup Diagram

The overall system architecture and power measurement configuration are illustrated in Figure 1, which depicts the ESP32 module, integrated agricultural sensors, LoRa communication module, dual digital multimeters, and regulated power supply used in this study.

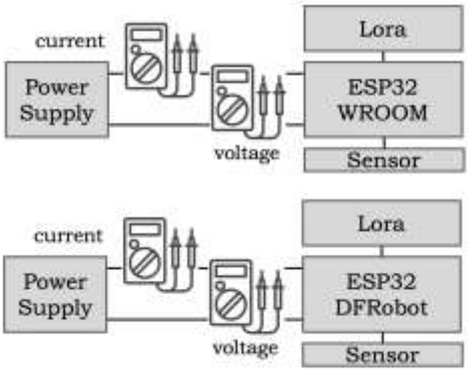

Figure 1 Experimental Setup Diagram

3. RESULTS AND DISCUSSIONS

The experimental evaluation reveals clear distinctions in power consumption behavior between ESP32 WROOM and ESP32 DFRobot modules, particularly when transitioning from normal operation to deep sleep mode. By applying identical hardware configurations, firmware logic, sensor workloads, LoRa communication parameters, and measurement procedures, the observed differences can be attributed primarily to module-level hardware design, rather than software-related factors.

3.1 Power Consumption Characteristics

Table 2 summarizes the measured mean and standard deviation (SD) of voltage, current, and power consumption for both ESP32 modules operating in normal mode and deep sleep mode. Each reported value represents the average of 50 measurement trials conducted under steady-state conditions..

Table 2. Measured Power Consumption of ESP32 Modules (Mean ± SD, n = 50)

Module	Operating Mode	Avg. Voltage (V)	Avg. Current (mA)	Avg. Power (mW)
ESP32 WROOM	Normal mode	3.323 ± 0.0017	86 ± 0.38	285.76 ± 1.168
ESP32 WROOM	Deep sleep mode	3.323 ± 0.0016	11.104 ± 0.0198	36.91 ± 0.073
ESP32 DFRobot	Normal mode	3.326 ± 0.0017	74.99 ± 0.986	249.42 ± 3.268
ESP32 DFRobot	Deep sleep mode	3.327 ± 0.0016	0.095 ± 0.00015	0.317 ± 0.00063

The results indicate that both ESP32 WROOM and ESP32 DFRobot exhibit comparable power consumption in normal mode, despite minor numerical differences. This similarity suggests that active-mode energy usage is largely governed by the shared ESP32 chipset architecture, including CPU operation, peripheral activity, multi-sensor data acquisition, and LoRa transmission. The observed variations remain within expected operational ranges for practical IoT deployments.

In contrast, a substantial divergence is observed in deep sleep mode. ESP32 DFRobot consistently demonstrates significantly lower residual current and power consumption than ESP32 WROOM. This result confirms that deep sleep performance is strongly influenced by module-level power regulation, power routing, and always-on circuitry, rather than by the ESP32 microcontroller core alone.

3.2 Relative Power Reduction Analysis

To further quantify the effectiveness of deep sleep mode, Table 3 presents the relative power reduction achieved when transitioning from normal mode to deep sleep mode for each module.

Table 3. Relative Power Reduction between Normal and Deep Sleep Modes

Module	Power (Normal) (mW)	Power (Deep Sleep) (mW)	Power Reduction (%)
ESP32 WROOM	285.76	36.91	87.08%
ESP32 DFRobot	249.42	0.317	99.87%

As shown in Table 3, both modules achieve high power reduction percentages, confirming the effectiveness of deep sleep mode for duty-cycled IoT operation. However, ESP32 DFRobot exhibits a substantially higher power reduction, indicating a more effective minimization of residual power consumption during idle periods.

3.3 Deep Sleep Power Efficiency Comparison

Beyond relative reduction within each module, a direct comparison of deep sleep power consumption highlights the magnitude of efficiency differences between the two ESP32 variants. Using the measured deep sleep power values, ESP32 DFRobot reduces deep sleep power consumption by approximately 99.14% relative to ESP32 WROOM.

This quantitative result explicitly identifies ESP32 DFRobot as the more power-efficient module during deep sleep operation and demonstrates how large the efficiency improvement is under identical operating conditions. Such a difference is particularly critical for IoT systems characterized by long idle intervals and infrequent data transmission.

Practical implications are quantified using a LiFePO4 battery (3.65 V, 6000 mAh, ≈21.9 Wh) under two duty-cycled configurations. For a cycle of 5 s active operation and 5 min deep sleep, the estimated energy per cycle is 0.00347 Wh for ESP32 WROOM and 0.000373 Wh for ESP32 DFRobot, corresponding to projected lifetimes of approximately 22.3 days and 207.4 days, respectively. When the deep sleep interval is extended to 10 min, the energy per cycle becomes 0.00655 Wh (ESP32 WROOM) and 0.000399 Wh (ESP32 DFRobot), yielding projected lifetimes of about 23.4 days and 384.1 days. These results indicate that in duty-cycled IoT systems, deep sleep power consumption dominates battery lifetime, and improvements at the module level translate directly into substantial operational lifetime gains.

3.4 Interpretation from a Hardware Design Perspective

The quantitative results in Tables 2 and 3 clearly demonstrate the impact of module-level hardware architecture on low-power performance. While normal mode power consumption remains similar due to the shared ESP32 chipset and identical sensor–LoRa workloads, deep sleep behavior differs markedly due to variations in onboard voltage regulators, power isolation strategies, and quiescent current characteristics.

The higher residual power consumption observed in ESP32 WROOM suggests that certain onboard components remain partially powered during deep sleep, limiting achievable energy savings. In contrast, ESP32 DFRobot appears to implement more aggressive power isolation and lower quiescent-current regulation, enabling more effective utilization of the ESP32 ultra-low-power domain.

3.5 Practical Implications for Low-Power IoT Deployment

From a system design perspective, these results demonstrate that module selection is a critical factor in energy-constrained IoT deployments. For applications dominated by long idle periods—such as agricultural monitoring, environmental sensing, and remote telemetry—the superior deep sleep efficiency of ESP32 DFRobot can significantly extend battery lifetime.

Conversely, for applications characterized by frequent processing or continuous operation, the relatively small difference in normal mode power consumption suggests that cost, availability, and ecosystem support—factors favoring ESP32 WROOM—may remain the primary selection criteria.

3.6 Limitations and Future Work

Despite the realistic multi-sensor and LoRa-based experimental setup, several limitations remain. First, experiments were conducted under controlled laboratory conditions; environmental factors such as temperature variation, supply voltage fluctuation, and long-term component aging were not considered. Second, only normal mode and deep sleep mode were evaluated, while intermediate power-saving states such as light sleep and modem sleep were not examined.

Future work will extend this study by evaluating additional ESP32 module variants, exploring intermediate low-power modes, and conducting long-term battery-powered field experiments under real agricultural conditions. Further investigation into hardware–firmware co-optimization and adaptive duty-cycling strategies under dynamic sensing and communication workloads also represents a promising direction for enhancing energy efficiency in ESP32-based IoT systems.

4. CONCLUSION

This study presents a comprehensive experimental comparison of power consumption characteristics between ESP32 WROOM and ESP32 DFRobot modules under realistic multi-sensor agricultural IoT operation using LoRa communication. By applying identical hardware configurations, firmware logic, sensor workloads, and measurement procedures, the analysis isolates the impact of module-level hardware design on power efficiency.

The experimental results demonstrate that both ESP32 modules exhibit comparable power consumption during normal mode operation, indicating that active-mode energy usage is primarily governed by the shared ESP32 chipset architecture and communication workload. However, a pronounced divergence is observed during deep sleep operation. ESP32 WROOM consumes 36.907 mW in deep sleep, whereas ESP32 DFRobot consumes only 0.317 mW.

A quantitative efficiency analysis reveals that ESP32 DFRobot achieves an approximately 99.14% reduction in deep sleep power consumption relative to ESP32 WROOM, clearly identifying ESP32 DFRobot as the more power-efficient module during idle periods. This substantial efficiency gap highlights the critical role of module-level power regulation, power routing, and always-on circuitry in determining ultra-low-power performance beyond microcontroller-level specifications.

These findings provide empirical evidence to support informed hardware selection for energy-constrained IoT applications. While ESP32 WROOM remains a practical choice for cost-sensitive deployments, applications with frequent active operation, or scenarios where availability and ecosystem support are dominant considerations, ESP32 DFRobot is better suited for long-term, battery-powered deployments dominated by extended sleep intervals. Therefore, module selection should be guided by the dominant operational profile rather than deep sleep efficiency alone.

Future work will prioritize the evaluation of intermediate power-saving modes, particularly light sleep and modem sleep, to bridge the gap between active and deep sleep operation in practical IoT systems. Subsequent extensions will consider the effects of supply voltage and temperature variations, as well as long-term battery-powered field testing, to further validate module-level power efficiency under real deployment conditions.

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