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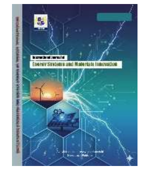

Design and Performance Analysis of an ESP32-Based Hybrid Charging System Using Solar Panels and USB Type-C for a Miniature Electric Vehicle

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Abstract

The development of renewable energy-based charging systems has become increasingly important in supporting sustainable electric vehicle technology. However, photovoltaic charging performance is highly influenced by weather conditions, affecting system reliability. This study aims to design and evaluate an ESP32-based hybrid charging system integrating solar panels and USB Type-C technology for miniature electric vehicles. The system comprises a solar panel, USB Type-C charging module, lithium-ion battery pack, Battery Management System (BMS), INA219 sensor, ESP32 microcontroller, Bluetooth communication, and motor control unit. Performance testing was conducted under three charging scenarios: solar charging during slightly cloudy conditions, solar charging under sunny conditions, and USB Type-C charging. Results showed that the solar panel generated 8.55 V without measurable current under cloudy conditions, producing 0 W output power. Under sunny conditions, the system produced 8.60 V, 0.18 A, and 0.90 W. In contrast, USB Type-C charging delivered 10.43 V, 3.20 A, and 33.37 W, equivalent to approximately 37 times higher power output. Furthermore, ESP32 successfully enabled real-time monitoring and Bluetooth-based wireless data transmission. The proposed system provides a practical, flexible, and cost-effective charging solution while supporting renewable energy utilization.

Keywords: *Hybrid Charging System; ESP32; Solar Panel; USB Type-C; Miniature Electric Vehicle.*

1. Introduction

The growing demand for energy and increasing concerns regarding the environmental consequences of fossil fuel utilization have encouraged the advancement of renewable energy technologies and electric transportation systems[1]. Electric vehicles (EVs) are widely recognized as an effective alternative for reducing greenhouse gas emissions and dependence on conventional energy sources[1]. Nevertheless, the successful implementation of EV technology requires charging systems that are efficient, reliable, and capable of supporting sustainable energy utilization. Among various renewable energy sources, solar photovoltaic (PV) technology has attracted significant attention due to its abundance, environmental compatibility, and capability to convert solar radiation directly into electrical energy.

Photovoltaic systems have been extensively applied in residential, commercial, and transportation sectors to decrease reliance on fossil-fuel-based electricity generation [2], [3]. Previous studies have indicated that integrating PV technology with EV charging infrastructure can support decentralized energy systems, reduce operational costs, and lower carbon emissions[1], [4]. Consequently, photovoltaic-based charging systems have become an important component in the development of sustainable mobility solutions.

Despite these advantages, the performance of photovoltaic charging systems is strongly influenced by environmental conditions. Variations in solar irradiance, ambient temperature, cloud cover, and weather patterns directly affect the electrical output of PV modules[2]. Under low-irradiance conditions, photovoltaic panels may still generate voltage; however, the available current and output power are considerably reduced[2], [3], resulting in lower charging efficiency. These characteristics limit the capability of standalone solar charging systems to provide continuous and reliable charging under varying environmental conditions.

To address this limitation, hybrid charging architectures have been developed by combining renewable energy sources with conventional charging methods[1]. Such systems enhance operational flexibility by utilizing complementary energy sources that can maintain charging continuity when solar energy production declines. Previous research has demonstrated that hybrid charging configurations can improve energy availability, charging reliability, and overall system performance while maintaining the benefits of renewable energy utilization[1].

Simultaneously, advancements in microcontroller technology have accelerated the development of intelligent monitoring and energy management systems. The emergence of the Internet of Things (IoT) enables real-time data acquisition, monitoring, and remote control of electrical systems[5], [6], [7]. Among available platforms, the ESP32 microcontroller has become widely adopted because of its integrated wireless communication capabilities, low implementation cost, and high processing performance[8]. In renewable energy applications, ESP32-based systems have been successfully employed for energy monitoring, smart management, and real-time acquisition of electrical parameters[2], [3], [9].

Accurate measurement of charging parameters is essential to evaluate system performance and ensure safe battery operation. Sensors such as the INA219 facilitate real-time monitoring of voltage and current[9], [10], enabling power calculation and performance assessment. The integration of ESP32 and INA219 provides a compact and cost-effective monitoring solution[5], [11], while Bluetooth communication enhances user accessibility through wireless data transmission to mobile devices.

Although previous studies have investigated photovoltaic charging systems, hybrid energy management approaches, and IoT-based monitoring technologies, research focusing on compact hybrid charging platforms for miniature electric vehicles remains limited. Furthermore, the integration of photovoltaic charging, USB Type-C charging, ESP32-based monitoring, Bluetooth communication, and motor control within a single system has not been extensively explored. Therefore, this study proposes the design and performance evaluation of an ESP32-based hybrid charging system for a miniature electric vehicle. The system integrates solar photovoltaic charging, USB Type-C charging, a lithium-ion battery pack, INA219 monitoring, Bluetooth communication, and motor control functions within a unified platform. The study aims to evaluate the electrical performance of each charging source under different operating conditions and assess the effectiveness of the monitoring system in providing real-time charging information. The proposed system is expected to contribute to the development of intelligent, economical, and sustainable charging solutions for small-scale electric mobility applications.

Materials and Methods

This study aimed to develop and evaluate an ESP32-based hybrid charging system integrating solar photovoltaic energy and USB Type-C charging technology for a miniature electric vehicle. The proposed system was designed to enhance charging flexibility by combining renewable and conventional energy sources while providing real-time monitoring of electrical parameters. System performance was assessed through experimental measurements of voltage, current, and power under different charging conditions, including photovoltaic charging under varying weather conditions and USB Type-C charging.

The hardware configuration comprised an ESP32 microcontroller, INA219 current-voltage sensor, USB Type-C DC-DC charging module for a 3S lithium battery pack, 20 A Battery Management System (BMS), three series-connected 3.7 V lithium-ion 18650 batteries, a solar panel, L298N motor driver, 12 V DC motor, jumper wires, and a power switch. The ESP32 served as the central controller for data acquisition, wireless communication, and motor operation[5]. Electrical parameters were measured using the INA219 sensor through the I2C communication protocol[9], [10], enabling simultaneous monitoring of voltage, current, and power with high measurement accuracy[12].

Table 1. Main Components of the Proposed System

Component	Specification
ESP32	Wi-Fi and Bluetooth-enabled microcontroller
INA219	Current and voltage monitoring sensor
Solar Panel	Renewable energy source
USB Type-C Charging Module	DC-DC charging converter for 3S battery
BMS 3S	Battery protection and management system
Lithium Battery	3 × 3.7 V 9900 mAh (3S configuration)
L298N	DC motor driver module
DC Motor	12 V miniature vehicle motor
Jumper Wires and Switch	Electrical connections

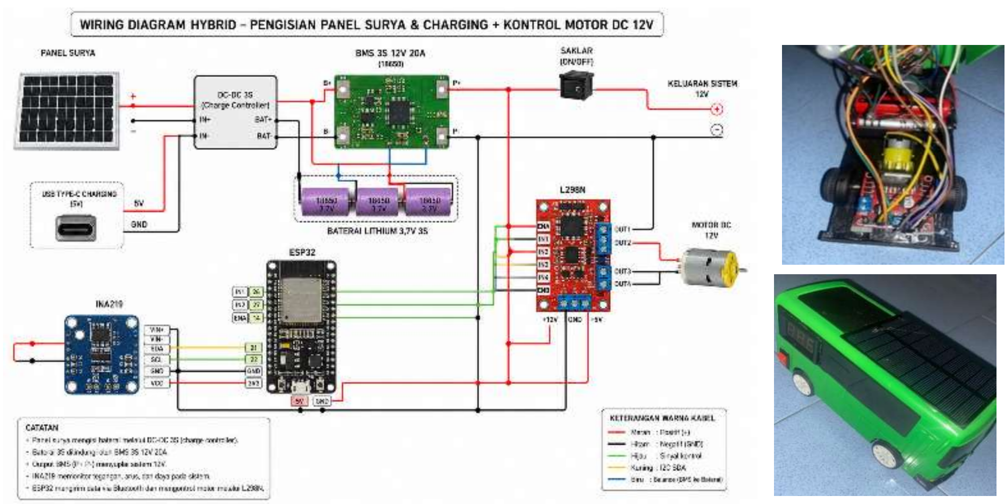

Figure 1. Overall Architecture of the ESP32-Based Hybrid Charging System

The charging architecture utilized two energy sources: a photovoltaic module and a USB Type-C charging unit. The photovoltaic source supplied renewable energy under adequate solar irradiance, whereas the USB charging module ensured charging continuity when solar generation was insufficient. Both sources were integrated through charging and protection circuits connected to the battery pack.

Voltage and current data acquired by the INA219 sensor were processed by the ESP32 to determine instantaneous power using:

$$P = V \times I \qquad [1]$$

where *P* represents power (W), *V* denotes voltage (V), and *I* indicates current (A)[13].

Measurement results were transmitted wirelessly via Bluetooth Serial communication[14], enabling smartphone-based monitoring of battery voltage, charging current, charging power, and charging status. Charging conditions were identified when current values exceeded 0.05 A.

The ESP32 also controlled vehicle movement through the L298N dual H-bridge driver, supporting forward, reverse, and stop commands transmitted via Bluetooth.

The software was developed using Arduino IDE and configured for Bluetooth communication, sensor acquisition, power calculation, and motor control. Monitoring data were updated at one-second intervals while command signals were processed concurrently.

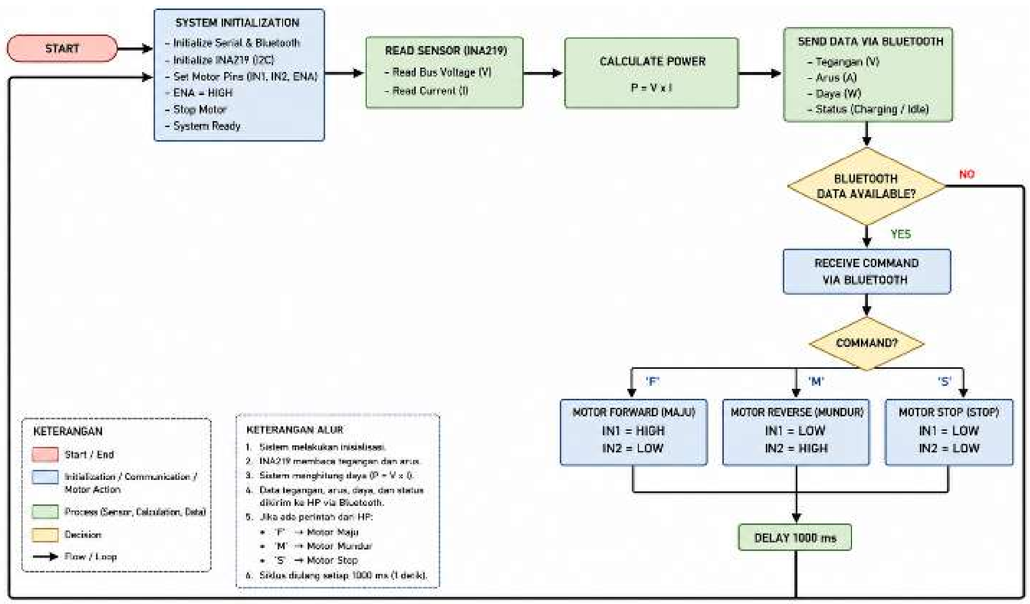

Figure 3. Program Flowchart of the Proposed System

Performance evaluation was conducted under three charging scenarios: photovoltaic charging under partially cloudy conditions, photovoltaic charging under higher solar irradiance, and USB Type-C charging. Recorded voltage, current, and power data were analyzed to assess charging effectiveness and overall system performance.

Results and Discussion

This section discusses the performance assessment of the proposed hybrid charging system based on ESP32, which integrates photovoltaic panels and USB Type-C charging for miniature electric vehicle applications. The evaluation emphasized the electrical performance of each charging source through the analysis of voltage, current, and power parameters. Data acquisition was performed using the INA219 sensor connected to the ESP32 microcontroller, while monitoring information was transmitted wirelessly via Bluetooth to enable real-time observation.

The development of the hybrid charging architecture was intended to address the operational constraints of single-source renewable energy charging systems. Although photovoltaic energy represents a sustainable and environmentally friendly alternative, its performance is highly dependent on solar irradiance and weather variability. Therefore, a USB Type-C charging module was incorporated as a supplementary energy source capable of delivering higher and more stable charging power when photovoltaic output decreases. Previous studies have demonstrated that combining multiple charging sources can enhance system reliability and energy availability.

1. Performance Evaluation of Solar Panel Charging

The initial experiment was conducted under slightly cloudy conditions to investigate the capability of the photovoltaic module to generate electrical energy during limited solar irradiation. The measurement results obtained through the INA219 sensor are presented in Table 2.

Table 2. Solar Panel Performance Under Different Weather Conditions

Condition	Voltage (V)	Current (A)	Power (W)
Slightly Cloudy	8.55	0.00	0.00
Sunny	8.60	0.18	0.90

Figure 4. Solar Panel Test Results in Slightly Cloudy Weather Conditions

Experimental observations indicate that the photovoltaic module produced an output voltage of 8.55 V under slightly cloudy conditions. However, no charging current was detected, resulting in zero power generation. These findings suggest that although open-circuit voltage was present, the available solar irradiance was insufficient to generate effective charging current for the battery. This behavior is consistent with photovoltaic theory, where reduced irradiance primarily affects current generation due to a lower number of photon-induced charge carriers[15].

The absence of charging current under cloudy conditions highlights a fundamental limitation of photovoltaic-based charging systems. Variations in environmental conditions significantly influence the energy conversion capability of solar modules[3], potentially reducing charging reliability during periods of low sunlight intensity. Consequently, the integration of an auxiliary charging source becomes necessary to ensure continuous system operation.

A subsequent experiment was performed under direct sunlight exposure. Under these conditions, the photovoltaic module generated 8.60 V, 0.18 A, and approximately 0.90 W of power. Compared with the previous test, the results demonstrate a substantial improvement in charging performance as solar irradiance increased.

Figure 5. Solar Panel Test Results Under Sunny Weather Conditions

The increase in current from 0.00 A to 0.18 A confirms the strong influence of solar irradiance on photovoltaic performance. While voltage exhibited only a marginal increase, current output improved considerably, indicating that current generation is more sensitive to irradiance fluctuations than voltage generation. Although the resulting power output remained relatively low compared with conventional charging methods, the photovoltaic module successfully contributed electrical energy to the charging process. This finding supports the feasibility of integrating renewable energy sources into small-scale electric transportation systems and extending battery operating duration while reducing dependence on external power infrastructure.

1 Performance Evaluation of USB Type-C Charging

The secondary charging source was evaluated using a USB Type-C charging module. The measured electrical characteristics are summarized in Table 3.

Table 3. USB Type-C Charging Performance

Charging Source	Voltage (V)	Current (A)	Power (W)
USB Type-C	10.43	3.20	33.37

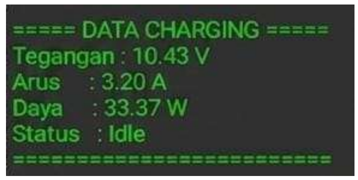

Figure 6. USB Type-C Charging Performance

The USB Type-C charging module exhibited substantially superior charging performance compared with the photovoltaic source. Measurements showed an output voltage of 10.43 V and a charging current of 3.20 A, resulting in a maximum power output of 33.37 W. The enhanced performance can be attributed to the stable energy supply provided by USB charging[13], which operates independently of environmental factors such as cloud cover and solar irradiance.

The reliability of USB Type-C charging enables a consistent and predictable charging process, making it particularly suitable for applications requiring uninterrupted battery replenishment. A comparison of power outputs further emphasizes the performance difference between the two charging methods. Based on experimental data, the USB Type-C module generated approximately 37 times more power than the solar panel under sunny conditions[16].

$$\text{Power Ratio} = \frac{33.37}{0.90} = 37.08 \quad [2]$$

These results indicate that USB Type-C charging provides a significantly faster charging mechanism than direct photovoltaic charging under the tested conditions[1].

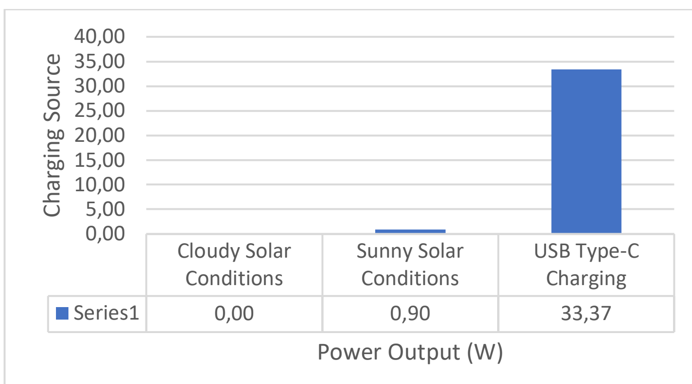

Figure 7. Comparison of Power Output from Different Charging Sources

The graphical comparison reveals a considerable disparity between renewable and conventional charging methods. While photovoltaic charging offers sustainability benefits, its performance remains highly dependent on environmental conditions. Conversely, USB Type-C charging consistently delivers higher power output suitable for rapid battery charging.

2 ESP32 Monitoring System Performance

Beyond charging performance evaluation, the effectiveness of the ESP32-based monitoring system was also investigated. The ESP32 successfully acquired voltage and current measurements from the INA219 sensor and transmitted the collected data through Bluetooth

Serial communication[5]. System parameters, including voltage, current, power, and charging status, were updated at one-second intervals.

The implemented software architecture enabled real-time monitoring using a smartphone device[3], [11], [17], thereby simplifying system supervision and minimizing reliance on external measurement equipment. Furthermore, Bluetooth communication enhanced portability and operational convenience, supporting its application in educational activities, research projects, and prototype development.

The charging-status algorithm embedded within the ESP32 software effectively distinguished between charging and idle conditions. A current threshold of 0.05 A was employed, where values exceeding the threshold were classified as charging, while lower values were categorized as idle. Experimental validation confirmed the accuracy of this approach during both photovoltaic and USB charging operations.

3 Overall Hybrid Charging System Analysis

The experimental findings demonstrate that the proposed hybrid charging system effectively integrates renewable and conventional energy sources within a single platform. Each charging method presents distinct advantages and limitations. Photovoltaic charging offers environmentally sustainable energy generation without dependence on external electrical infrastructure; however, its performance is strongly affected by weather conditions and irradiance variability. In contrast, USB Type-C charging provides superior power output and operational stability but requires access to an external electrical source.

The combination of both charging mechanisms improves charging flexibility and system reliability[1]. During periods of adequate sunlight, photovoltaic energy can contribute to battery charging, whereas USB Type-C charging ensures continuity when solar energy becomes unavailable or insufficient. Consequently, the hybrid strategy enhances system availability while supporting sustainable energy utilization.

In addition, the integration of ESP32, INA219, Bluetooth communication, and motor-control functionality demonstrates the practicality of implementing intelligent charging systems for miniature electric vehicles. The developed prototype successfully combines energy harvesting, battery charging, wireless monitoring, real-time communication, and vehicle control within a compact and cost-effective platform[9]. These characteristics indicate significant potential for educational laboratories, renewable energy demonstrations, prototype development, and future small-scale electric mobility applications.

Conclusion

This study successfully developed and evaluated an ESP32-based hybrid charging system integrating solar photovoltaic technology and USB Type-C charging for miniature electric vehicle applications. The proposed architecture combines renewable energy harvesting, battery charging, real-time monitoring, wireless communication, and motor control within a unified platform.

Experimental findings revealed that photovoltaic charging performance was strongly influenced by environmental conditions. Under slightly cloudy weather, the solar panel generated an output voltage of 8.55 V without detectable charging current, resulting in zero power output. Conversely, under higher solar irradiance, the system produced 8.60 V, 0.18 A, and 0.90 W, indicating that photovoltaic energy can effectively support battery charging when adequate sunlight is available. However, charging capability decreases significantly under low-irradiance conditions.

The USB Type-C charging module demonstrated superior performance, delivering 10.43 V, 3.20 A, and 33.37 W. This output was approximately 37 times greater than that of the solar charging mode, enabling faster and more stable charging. Consequently, the integration of both charging sources enhances charging flexibility and improves energy availability under varying environmental conditions.

Furthermore, the ESP32 successfully processed INA219 sensor measurements and transmitted charging information via Bluetooth in real time. Overall, the proposed hybrid charging system represents a cost-effective and intelligent solution with potential applications in education, renewable energy demonstrations, and future small-scale electric mobility systems.

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References

[1] P. Bastida-Molina, E. Hurtado-Perez, M. C. M. Gomez, and C. Vargas-Salgado, "Multicriteria design and experimental verification of hybrid renewable energy systems. Application to electric vehicle charging stations," *ArxiV.org*, Mar. 2021, Accessed: Jun. 16, 2026. [Online]. Available: https://arxiv.org/pdf/2103.16976

[2] Z. Permana Muqorrobin, A. Nawawi, A. A. Ardani, S. Putra Setia, R. Rahmadian, and M. Mustapha, "Off-Grid Solar System Monitoring Based on ESP-32 and INA219 in Pesanggrahan Gordomulyo," *Vokasi UNESA Bulletin of Engineering, Technology and Applied Science*, vol. 1, no. 2, pp. 26–37, Dec. 2024, doi: 10.26740/VUBETA.V1I2.34859.

[3] F. A. Silaban, E. Nur, W. Putra, and L. M. Silalahi, "Monitoring and Evaluation Electrical Power Control in Solar Power Systems Based on IoT," *CCIT (Creative Communication and Innovative Technology) Journal*, vol. 17, no. 2, pp. 170–183, May 2024, doi: 10.33050/CCIT.V17I2.2996.

[4] Z. Liang and Y. Guo, "Smart Charging and Parking of Plug-in Hybrid Electric Vehicles in Microgrids Considering Renewable Energy Sources," Jul. 2018, Accessed: Jun. 17, 2026. [Online]. Available: https://arxiv.org/pdf/1807.05628

[5] A. El, H. Lubis, and R. Kurniawan, "Implementasi Konsumsi Energi Listrik Perabotan Rumah Tangga Berbasis IoT Menggunakan ESP-32, Sensor PZEM 004T dan Fuzzy Mamdani," *CESS (Journal of Computer Engineering, System and Science)*, vol. 11, no. 1, pp. 218–232, Feb. 2026, doi: 10.24114/CESS.V11I1.72255.

[6] W. Yuniarto, M. Diponegoro, E. Program Studi Teknik Elektro, P. Negeri Pontianak, K. Barat, and K. Kunci, "RANCANG BANGUN SISTEM MONITORING DAN KONTROL ENERGI LISTRIK PADA BEBAN 3 FASA MENGGUNAKAN ESP32 BERBASIS INTERNET OF THINGS (IOT)," *Jurnal Poli-Teknologi*, vol. 22, no. 1, pp. 30–38, Jan. 2023, doi: 10.32722/PT.V22I1.5102.

[7] T. M. Aritonang, K. C. M. siregar, A. T. Darmawan, E. D. Suryanto, and D. P. Saragi, "PROTOTYPE SMART IOT SAFETY AND ENERGY MONITORING SYSTEM BERBASIS ESP32 UNTUK MONITORING DAN PROTEKSI INSTALASI LISTRIK SECARA REAL-TIME," *JOURNAL SAINS STUDENT RESEARCH*, vol. 4, no. 2, pp. 160–170, Apr. 2026, doi: 10.61722/JSSR.V4I2.9445.

[8] "ESP32 Datasheet." Accessed: Jun. 17, 2026. [Online]. Available: https://documentation.espressif.com/esp32_datasheet_en.html?utm_source=chatgpt.com

[9] M. F. Abdillah, M.Nawawi, and R. Maulidda, "Portable Solar Panel Using IoT for Monitoring Current and Voltage using ESP32," *Journal of Artificial Intelligence and Engineering Applications (JAIEA)*, vol. 5, no. 1, pp. 361–366, Oct. 2025, doi: 10.59934/JAIEA.V5I1.1327.

[10] W. He, M. J. A. Baig, and M. T. Iqbal, "An Open-Source Supervisory Control and Data Acquisition Architecture for Photovoltaic System Monitoring Using ESP32, Banana Pi M4, and Node-RED," *Energies 2024, Vol. 17, Page 2295*, vol. 17, no. 10, p. 2295, May 2024, doi: 10.3390/EN17102295.

[11] M. Khoerudin, S. Watmah, and D. Direvisi Disetujui, "Pemantauan Catu Daya untuk Proteksi Listrik Menggunakan ESP32 Berbasis Internet of Things (IOT)," *IMTechno: Journal of Industrial Management and Technology*, vol. 6, no. 2, pp. 94–99, Jul. 2025, doi: 10.31294/IMTECHNO.V6I2.9518.

[12] G. de C. Bertoli, G. V. C. Fernandes, P. H. B. Monici, C. H. de A. Guibo, L. A. Pereira, and A. Santos, "Design and implementation of intelligent packet filtering in IoT microcontroller-based devices," *Journal of Internet Services and Applications*, vol. 15, no. 1, pp. 289–301, May 2023, doi: 10.5753/jisa.2024.3835.

[13] M. Giesselmann, "Computer Simulation of Power Electronics and Motor Drives," *Power Electronics Handbook*, pp. 1365–1385, Jan. 2023, doi: 10.1016/B978-0-323-99216-9.00030-5.

[14] V. B. Vales, O. C. Fernández, T. Domínguez-Bolaño, C. J. Escudero, and J. A. García-Naya, "Fine Time Measurement for the Internet of Things: A Practical Approach Using ESP32," *IEEE Internet Things J.*, vol. 9, no. 19, pp. 18305–18318, Jan. 2024, doi: 10.1109/JIOT.2022.3158701.

[15] W. A. Beckman, N. Blair, and J. A. Duffie, "Solar Engineering of Thermal Processes, Photovoltaics and Wind, Fifth Edition," *Solar Engineering of Thermal Processes, Photovoltaics and Wind, Fifth Edition*, pp. 1–905, Jan. 2021, doi: 10.1002/9781119540328.

[16] J.-K. Zhou, J. Liu, and G.-M. Cai, "Impact and Analysis of Different Charging Methods on Battery Lifespan A Charging Control Program (C Language) to Reduce Battery Degradation," Oct. 2025, doi: 10.21203/RS.3.RS-7698899/V1.

[17] P. Pujianto, M. T. Tendean, and M. Z. Z. Muhtadi, "Sistem Monitoring Energi Listrik 3 Fasa Berbasis IoT Dengan Protokol Modbus RS-485 Menggunakan ESP32," *Journal of Instrumentation and Hardware*, vol. 3, no. 2, pp. 1–10, Dec. 2025, doi: 10.53026/INHARDWARE.V3I2.72.