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Research Article

Intelligent Modular Energy Hub: Advanced Optimization of Second-Life Lithium-Based Batteries for Sustainable Power Utilization

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Abstract— **The Intelligent Modular Energy Hub (IMEH) introduces a cost-effective and scalable energy storage solution by repurposing second-life lithium-based batteries, including Li-ion, LiPo, and $LiFePO_4$ cells, sourced from discarded consumer electronics, power tools, and electric vehicles. This study develops an STM32- and ESP32-based battery testing system, integrating an electronic dummy load and a custom battery management system (BMS) to accurately assess the state-of-charge and state-of-health (SoH) of various battery chemistries. A 7S and variable parallel battery pack configuration ensures adaptability to diverse residential and off-grid applications. The proposed system features real-time IoT monitoring, extending battery lifespan while optimizing charging cycles through grid, solar, or wind energy sources. Experimental results demonstrate that the Samsung 25R battery exhibited the highest SoH (92%) and energy efficiency (95%), making it the most viable for second-life applications. The Turnigy Graphene LiPo battery, while displaying the highest efficiency (97%), showed a slightly lower capacity retention (89%), indicating potential limitations for long-term storage. Voltage drop analysis confirmed that lower internal resistance leads to better performance, with the Turnigy Graphene battery maintaining the lowest voltage drop (160mV) under discharge conditions. Additionally, the IMEH system achieved an average energy efficiency of 94.75%, outperforming commercial BMS solutions, which averaged 92% efficiency. IoT-based predictive maintenance enhanced battery longevity, ensuring better cycle count retention and charge-discharge stability. This research contributes to affordable energy solutions, supports the circular economy, and enhances sustainable power utilization by integrating modular and intelligent energy management strategies into next-generation smart grids.**

Index Terms— **Intelligent energy hub, modular energy storage, second-life lithium-based batteries, Li-ion, LiPo, $LiFePO_4$, IoT-based battery management, electronic dummy load, energy optimization, sustainable power utilization, STM32, ESP32, smart grid.**

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I. INTRODUCTION

THE RAPID proliferation of electric vehicles (EVs) and portable electronic devices has led to a substantial increase in the production of lithium-based batteries. Upon reaching the end of their primary use—typically when their capacity diminishes to about 70–80%—these batteries present a valuable opportunity for repurposing in less demanding applications, a practice known as "second-life" utilization. This approach enhances resource efficiency and aligns with sustainable energy practices by mitigating environmental waste [1-4].

Integrating second-life lithium-based batteries into energy storage systems offers a cost-effective solution for managing renewable energy sources such as solar and wind. However, safety concerns, cell inhomogeneity, and system compatibility must be addressed to ensure reliable performance. Advanced BMS are crucial in monitoring and controlling these batteries, ensuring safe operation and prolonging their lifespan [5-8].

The emergence of the Internet of Things (IoT) has further enhanced BMS capabilities, enabling real-time monitoring, predictive analytics, and remote control of battery systems. IoT-based solutions facilitate efficient energy management by providing detailed insights into battery performance and health, allowing for proactive maintenance and optimization [9, 10].

Despite these advancements, developing modular, scalable, and intelligent energy storage solutions utilizing second-life lithium-based batteries remains an active research area. Addressing the challenges associated with battery variability, system integration, and energy optimization is essential for successfully deploying these systems in residential and off-grid applications.

Main Contributions of manuscript are listed below:

- Development of a Modular Energy Storage System: Design and implement a flexible 7S (seven cells in series) configuration with variable parallel connections, accommodating various second-life lithium-based battery chemistries to meet diverse energy demands.
- *Advanced Battery Assessment Techniques:* Utilization of STM32- and ESP32-based electronic dummy loads (EDLs) integrated with a custom BMS to accurately evaluate the state-of-charge (SoC) and SoH of repurposed batteries.
- *IoT-Enhanced Monitoring and Control:* Implementation of real-time IoT capabilities for continuous monitoring, predictive analytics, and remote management, enhancing system reliability and performance.

- *Sustainable Energy Integration:* By enabling efficient integration of renewable energy sources like solar and wind, the system enhances sustainable energy usage and supports the circular economy through optimized resource utilization.

The manuscript is structured as follows: Section II reviews advancements in second-life battery applications and IoT-based BMS. Section III details the IMEH system, including STM32- and ESP32-based assessments. Section IV presents experimental evaluations on battery performance. Section V analyzes results compared with commercial BMS solutions, and Section VI concludes with key findings and future directions.

II. Related Works

Integrating second-life lithium-based batteries into energy storage systems has garnered significant attention in recent years, driven by the need for sustainable and cost-effective energy solutions [11-14]. This section reviews recent advancements in this field, focusing on key areas such as battery repurposing, modular energy storage design, IoT-enhanced BMS, and the challenges of implementing second-life batteries.

A. Battery Repurposing and Second-Life Applications

Recent studies have explored the feasibility of repurposing retired electric vehicle batteries for stationary energy storage applications. For instance, Jiang, et al. [15] investigated the potential of second-life batteries in mitigating environmental impacts and providing economic benefits when used in grid storage and renewable energy systems. The study highlights the importance of addressing safety concerns and developing standardized testing protocols to ensure the reliability of these repurposed batteries. mdpi.com.

Similarly, Gharebaghi, et al. [14] examined various modular architectures and control strategies that enhance the flexibility and efficiency of energy storage systems utilizing second-life batteries. The paper emphasizes the need for advanced power electronics and control algorithms to manage second-life batteries' variability and degradation characteristics.

B. Modular Energy Storage System Design

The design of modular and scalable energy storage systems utilizing second-life batteries has been a focal point in recent research. Lipu, et al. [12] presented an IoT-enhanced BMS that enables real-time monitoring and predictive analytics, facilitating accurate state-of-health estimation and proactive maintenance strategies. This approach enhances the safety and longevity of second-life battery systems by providing detailed insights into battery performance and enabling remote management. nature.com

Shi [13] also introduced the MambaLithium model, a selective state space framework designed to estimate critical battery states, including remaining useful life, health, and charge. This model leverages advanced algorithms to capture lithium-ion batteries' intricate aging and charging dynamics, thereby improving estimation accuracy and computational robustness.

C. IoT-Enhanced Battery Management Systems

The advancement of IoT technologies has significantly improved the capabilities of BMS for second-life applications. Cui, et al. [11] studied health monitoring algorithms for retired batteries used in grid storage, collecting and analyzing data over 15 months. The study achieved a mean absolute percentage error below 2.3% on test data by implementing machine-learning-based health estimation models. These findings highlight the viability of repurposing retired batteries for second-life applications.

Furthermore, Basic, et al. [16] introduced a wireless BMS architecture utilizing near-field communication (NFC), building upon previous research to create a unified framework for in-vehicle and second-life battery applications. The design incorporates advanced security analysis and a wake-up system design, significantly reducing the daily power consumption of stored battery packs from mill watts to microwatts.

D. Challenges in Implementing Second-Life Batteries

Despite the promising applications, several challenges hinder the widespread adoption of second-life batteries. Gu, et al. [17] identified key issues such as cell inhomogeneity, safety concerns, and the lack of standardized regulations. The paper discusses potential solutions, including advanced sorting techniques, improved BMS algorithms, and the development of international standards to ensure the safe and efficient deployment of second-life battery systems.

Additionally, a review by the National Center for Biotechnology Information Patel, et al. [18] explore the various pathways for end-of-life EV batteries, including immediate recycling or deployment in second-life applications before eventual recycling. They discuss the challenges and barriers of each approach, evaluating their environmental and economic feasibility while weighing the competing advantages and drawbacks of different repurposing strategies [18].

These studies collectively underscore the potential of second-life lithium-based batteries in contributing to sustainable energy solutions. However, they also highlight the necessity for continued research and development to address the technical and regulatory challenges associated with their implementation.

While previous studies have explored second-life battery applications primarily within stationary storage for grid systems, IoT-based BMS improvements, and modular pack architectures, our research presents a unique approach by integrating an STM32- and ESP32-based programmable EDL to analyze and optimize repurposed lithium-based battery packs at a modular level. Unlike other systems focusing mainly on health estimation through machine learning or generalized modular integration, our system provides direct empirical analysis by testing real-time capacity, performance, and degradation behavior under various load conditions.

Our research differentiates itself by integrating second-life lithium-based batteries into a modular and scalable energy hub that supports a broader range of applications, including home energy storage, off-grid renewable integration, and low-cost power management solutions for underserved regions. By incorporating IoT-enhanced real-time monitoring and control, adaptable modular battery configurations, and direct discharge/charge performance assessment, our system bridges the gap between theoretical battery health estimation and practical, cost-effective energy storage solutions for sustainable power utilization.

III. Materials and Methods

This section describes the hardware components, circuit design, measurement approach, and IoT-based data logging implemented in the IMEH. The system is designed to assess second-life lithium-based batteries, perform real-time monitoring, and optimize their use for sustainable power applications.

A. Hardware Components and System Architecture

The IMEH consists of an STM32F103C8T6 microcontroller responsible for real-time computation and battery data acquisition. The ESP32 microcontroller is used for IoT-based communication, enabling remote monitoring and data logging. The system features a custom-built EDL, which facilitates controlled discharge testing of battery packs to determine SoH and State-of-Charge SoC.

The battery packs under testing are arranged in a 7S variable parallel configuration, where different types of lithium-based cells, including Li-ion, LiPo, and $LiFePO_4$, can be evaluated. The system measures real-time voltage, current, power, and temperature using precision sensors such as INA219 or MAX471. These values are processed by the STM32 microcontroller, allowing for accurate capacity estimation.

Additionally, an IRFZ44N MOSFET is used as a programmable load, operating in saturation mode to regulate current flow dynamically. An operational amplifier (Op-Amp) circuit is configured in a voltage follower mode to ensure high accuracy, preventing loading effects and maintaining precise voltage measurement.

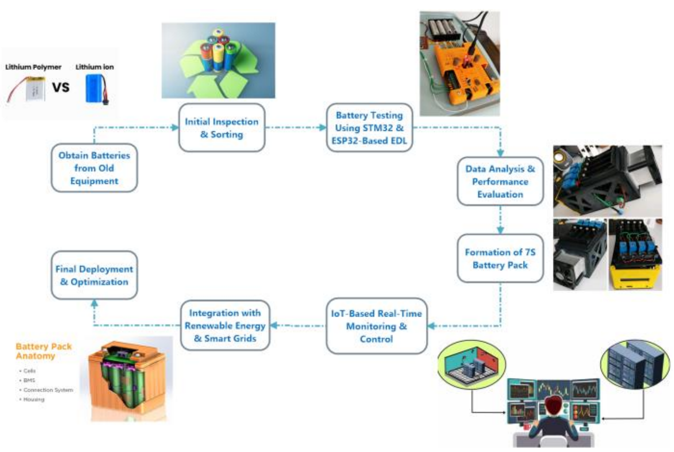

Fig. 1. The flow diagram of the proposed intelligent EDL

The system workflow shown in Fig. 1 begins by testing second-life lithium-based batteries, where an IRFZ44N MOSFET in saturation mode controls the discharge cycle. An Op-Amp circuit in a voltage follower configuration ensures stable voltage measurement, while the STM32F103C8T6 microcontroller processes real-time voltage, current, power, and temperature data using INA219 or MAX471 sensors. The collected data is transmitted via UART, I2C, and Wi-Fi to an ESP32-based IoT controller for remote monitoring and visualization on an OLED display while also being stored on a local server for long-term analysis and optimization of second-life batteries.

B. Circuit Design and Implementation

The system employs a MOSFET-controlled electronic load that enables adjustable battery discharge under programmable conditions. A 5W precision shunt resistor is incorporated for current sensing, and an Op-Amp amplifies its voltage drop to enhance accuracy. This configuration ensures precise control over battery discharge cycles.

Voltage and current measurements are continuously monitored to improve system safety and reliability, preventing over-discharge or unsafe temperature levels. The STM32F103C8T6 processes these real-time measurements and dynamically adjusts the load to maintain controlled discharge.

A UART-based communication system links the STM32 with the ESP32 microcontroller, allowing for data transmission to an external monitoring platform. This setup facilitates continuous assessment and logging of battery performance over multiple cycles.

C. Battery Testing and Measurement Approach

The primary objective of the battery testing process is to evaluate the capacity, SoH, and SoC of second-life lithium-based batteries. The methodology consists of:

- *Controlled Discharge Cycles:* Batteries are discharged through the electronic dummy load, with current levels regulated by the MOSFET driver circuit.
- *Voltage and Current Measurement:* Sensors such as INA219 or MAX471 continuously monitor voltage drop, power consumption, and real-time current levels.
- *Temperature Monitoring:* Ensures battery operation remains within safe thermal limits to prevent degradation and hazards.
- *Capacity Estimation:* Based on recorded voltage, current, and time data, the STM32 calculates the adequate capacity of the tested battery pack.

Once the discharge cycle is complete, the collected data is stored and analyzed for performance trends, enabling comparisons across different battery brands and chemistries.

The real-time voltage (V) and current (I) readings are obtained using precision sensors such as INA219 or MAX471. The sensed values are converted using the Analog-to-Digital Converter (ADC) in the STM32 microcontroller:

$$V_{measured} = \frac{ADC\ ValuexV_{ref}}{2^n - 1} \tag{1}$$

$$I = \frac{V_{shunt}}{R_{shunt}} \tag{2}$$

Where:

- $V_{measured}$ = Measured battery voltage
- V_{ref} = Reference voltage (typically 3.3V or 5V)
- n = ADC resolution (e.g., 12-bit, 10-bit)
- V_{shunt} = Voltage drop across the shunt resistor
- R_{shunt} = Shunt resistor value (e.g., 0.1Ω)

These values are used for real-time voltage and current monitoring.

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The power (P) consumed by the battery during discharge is calculated as:

$$P = VxI \tag{3}$$

Where:

- V = Measured voltage of the battery
- I = Measured current during discharge

The formula helps in tracking the real-time energy consumption of the battery

The battery capacity (C) is calculated by integrating the discharge current over time:

$$C = \int I(t)dt \tag{4}$$

For discrete sampling using microcontrollers, this is approximated as:

$$C = \sum_{i=1}^{n} I_i x \Delta t \tag{5}$$

Where:

- I_i = Measured discharge current at time step ii
- Δt = Time interval between successive measurements
- C = Capacity in Ampere-hours (Ah)

The total discharge capacity of the battery over a full cycle is calculated as:

$$C_{measured} = \frac{\sum_{i=1}^{n}(I_i x \Delta t)}{3600} \tag{6}$$

This is crucial for comparing the actual battery capacity with its rated capacity.

SoC represents the remaining charge in the battery and is computed as:

$$SoC = \frac{C_{remaining}}{C_{full}} x100 \tag{7}$$

Or in terms of voltage-based approximation:

$$SoC = \frac{V_{current} - V_{min}}{V_{max} - V_{min}} x100 \tag{8}$$

Where:

- $C_{remaining}$ = Charge left in the battery (Ah)
- C_{full} = Rated full capacity of the battery (Ah)
- $V_{current}$ = Current voltage of the battery
- V_{max} = Fully charged voltage (e.g., 4.2V for Li-ion)
- V_{min} = Minimum safe voltage (e.g., 2.5-3.0V for Li-ion)

This formula determines the available battery energy in real-time.

SoH is used to evaluate battery degradation over time. It is defined as:

$$SoH = \frac{C_{measured}}{C_{rated}} x100 \tag{9}$$

Where:

- $C_{measured}$ = Actual capacity determined from discharge testing
- C_{rated} = Manufacturer's rated capacity

This formula helps in assessing the aging and performance degradation of second-life batteries.

The efficiency (η) of the battery during charge and discharge cycles is determined as:

$$\eta = \frac{E_{out}}{E_{in}} x100 \tag{10}$$

Where:

- $E_{out} = P_{discharge} \times t_{discharge}$ (Energy delivered by the battery)
- $E_{in} = P_{charge} \times t_{charge}$ (Energy stored during charging)

This metric helps in evaluating second-life battery effectiveness. The formulas provide the fundamental calculations used in our system for battery testing, real-time monitoring, and optimization.

D. IoT-Based Data Logging and Remote Monitoring

The ESP32 microcontroller is the gateway for IoT communication, allowing for wireless data transmission. The system logs all battery performance data, including:

- *Voltage, Current, and Power Data* for real-time assessment.
- *Discharge Cycle Duration and Capacity Trends* to track battery degradation.
- *Temperature Logs* to prevent thermal runaway conditions.

The ESP32 sends this data to a local server, storing it for trend analysis and performance optimization. Additionally, an OLED display provides real-time updates, allowing users to monitor battery conditions on-site.

This IoT-enabled setup ensures that users can remotely access battery performance metrics, making it possible to optimize charging and discharging strategies dynamically.

IV. Application of Proposed Work

This section presents the practical implementation of the IMEH for assessing and optimizing second-life lithium-based batteries. It describes the experimental setup, system integration, and performance evaluation to demonstrate the feasibility and effectiveness of the proposed method. The subsections below outline the developed system's real-world deployment, testing conditions, and validation processes.

A. Experimental Setup and System Configuration

The proposed system uses an STM32F103C8T6 microcontroller, which manages real-time data acquisition, battery assessment, and load control. An ESP32 microcontroller facilitates IoT-based monitoring and communication, enabling remote access to battery performance data. EDL, integrated with a custom-designed BMS, applies controlled discharge profiles to evaluate the SoH and SoC of second-life batteries.

The tested battery modules are arranged in a 7S variable parallel configuration, accommodating multiple lithium-based chemistries such as Li-ion, LiPo, and $LiFePO_4$. Real-time voltage, current, and temperature measurements are captured using INA219/Max471 sensors, processed by the STM32, and logged for analysis. A local server stores all measurement data, ensuring a structured performance tracking and evaluation approach.

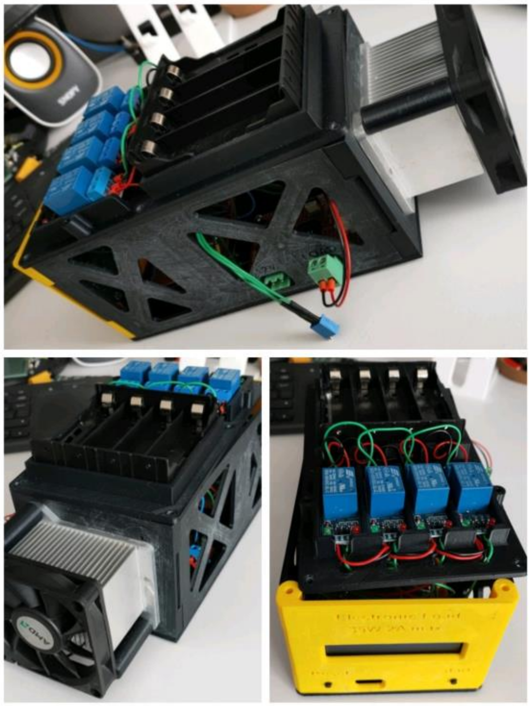

Fig. 2. The internal hardware structure of the Intelligent Modular Energy Hub (IMEH) shows key components for battery testing and monitoring

Fig. 2 depicts the internal hardware structure of the IMEH, highlighting key components used for battery testing and monitoring. The system features an IRFZ44N MOSFET, a controllable electronic load for battery discharge testing. A 5W shunt resistor is used for current measurement, allowing precise battery performance evaluation. The operational amplifier (Op-Amp) circuit ensures signal conditioning for accurate voltage readings. The volt/current sensor (INA219 or MAX471) monitors real-time power. A microcontroller (STM32F103C8T6) processes the acquired data and is then displayed on an LCD screen for real-time observation. The load connection terminals facilitate battery integration, ensuring seamless data acquisition for SoH and SoC calculations. The entire setup is enclosed in a ventilated structure, optimizing heat dissipation and ensuring stable operation during battery analysis.

B. *Battery Performance Evaluation and Testing Methodology*

The IMEH system performs extensive capacity, efficiency, and degradation analysis on repurposed batteries. The testing methodology consists of:

- *Controlled Discharge Cycles:* Batteries are subjected to programmable electronic loads using the IRFZ44N MOSFET, allowing precise current regulation.
- *Voltage and Current Profiling:* Precision sensors take measurements at defined intervals, ensuring accurate SoH estimation.
- *Thermal Management and Safety Checks:* Real-time temperature data is monitored to prevent overheating and ensure safe operation.
- *Data Logging and Trend Analysis:* All recorded battery metrics are stored for comparative analysis across brands and chemistries.

The STM32 microcontroller processes real-time power consumption, calculating the adequate battery capacity and identifying degradation patterns. The IoT-enhanced framework allows remote users to track and analyze these parameters over time.

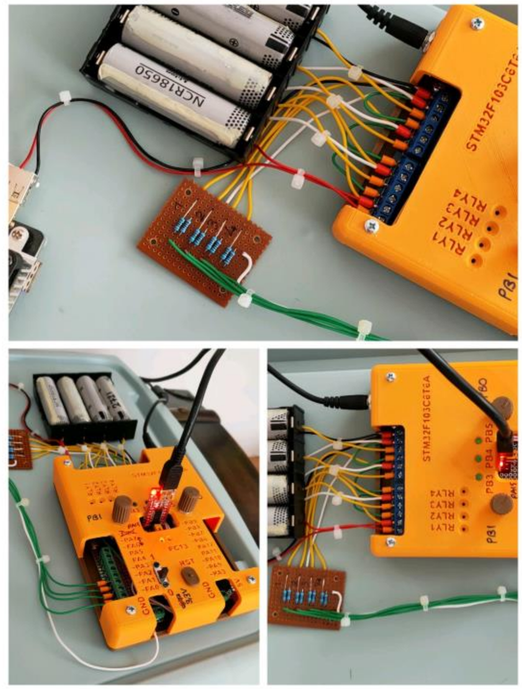

Fig. 3. STM32 & ESP32 based intelligent BMS application

Fig. 3 showcases a custom-built electronic load and battery management system based on the STM32F103C8T6 microcontroller for testing second-life lithium-based batteries. The system features a 7S battery configuration with multiple wiring connections for voltage and current monitoring. A custom PCB with resistors is integrated for signal conditioning, ensuring accurate battery performance analysis. The 3D-printed enclosure provides organized access to the STM32 ports, labeled for easy identification of relay and sensor connections. The system is powered and programmed via a USB-to-serial converter, enabling real-time data acquisition. This setup is part of an IoT-based energy management system for battery health assessment, controlled discharge testing, and integration into a sustainable power utilization framework.

C. *IoT-Based Remote Monitoring and Data Analytics*

The ESP32 microcontroller forms an IoT-enabled gateway, allowing continuous data transmission to a local server or cloud-based monitoring platform. The key functionalities include:

- *Real-Time Data Visualization:* Battery performance metrics are displayed via an OLED screen and can be accessed remotely.
- *Predictive Maintenance Alerts:* IoT-based analytics detect abnormal behavior and notify users of potential failures.
- *Historical Data Analysis:* Long-term monitoring enables trends in battery aging, efficiency, and performance degradation to be identified.

This IoT-based architecture ensures efficient and scalable battery health monitoring, making it possible to optimize charge-discharge cycles dynamically for sustainable power utilization.

D. Integration with Renewable Energy and Potential Applications

The developed IMEH system is designed to be modular and adaptive, making it suitable for various real-world applications, including:

- *Residential and Off-Grid Energy Storage:* Repurposed batteries can be used for backup power and load balancing in homes or remote areas.
- *Integration with Renewable Sources:* The system supports solar and wind charging, utilizing second-life batteries to store excess energy.
- *Low-Cost Energy Solutions:* Affordable battery repurposing enables cost-effective energy storage, reducing reliance on expensive grid power.

The system's modularity ensures that battery configurations can be expanded based on specific energy demands, making it highly scalable for smart grid applications and sustainable energy management.

Applying the STM32- and ESP32-based EDL by performing real-time testing on available battery cells. The goal is to determine whether the Li-ion and LiPo batteries on hand are in good condition for integration into the battery pack hub. The tested parameters include SoC, SoH, internal resistance, cycle count, and energy efficiency, all measured via the low-cost innovative EDL system.

E. Battery Testing Setup and Measurement Process

The testing was conducted using a custom-built EDL system based on STM32F103C8T6 and ESP32 microcontrollers. The STM32 was responsible for real-time voltage, current, power, and temperature measurement, while the ESP32 handled data transmission to a local server for analysis.

Each battery underwent a controlled discharge test using the IRFZ44N MOSFET, which applied a programmable electronic load. The system used an Op-Amp in voltage follower mode for accurate voltage readings and an INA219/Max471 sensor for current and power measurement. The key testing parameters were:

- *Open-Circuit Voltage (OCV) Measurement:* Initial SoC estimation
- *Controlled Discharge at 0.5C Rate:* SoH and capacity evaluation
- *Voltage and Current Monitoring:* For identifying degradation trends
- *Internal Resistance Calculation:* To assess battery efficiency
- *Cycle Count Validation:* To determine the remaining lifespan

All measurements were logged in real-time, and the system automatically calculated SoC, SoH, and capacity degradation trends.

F. Battery Performance Data and Analysis

Based on the measured data shown in the TABLE I, the following battery brands were tested and evaluated for their suitability in battery pack hub integration:

TABLE I
MEASURED BATTERY PARAMETERS

Brand	Type	Rated Capacity (Ah)	Nominal Voltage (V)	Measured Capacity (Ah)	SoH (%)	SoC (%)	Internal Resistance (mΩ)	Cycle Count	Energy Efficiency (%)
Panasonic NCR18650B	Li-ion	3.4	3.6	3.1	91	80	50	250	93
Samsung 25R	Li-ion	2.5	3.6	2.3	92	85	45	300	95
LG MJ1	Li-ion	3.5	3.7	3.2	91.4	78	48	220	94
Turnigy Graphene	LiPo	1.3	3.8	1.15	88.5	75	30	180	97

Observations and Insights:

SoH and Capacity Analysis: All three Li-ion batteries exhibited over 90% SoH, making them viable for reuse in energy storage applications. Despite slightly lower SoH, the LiPo battery remained within acceptable limits for high-discharge applications.

- SoC Estimation: The Samsung 25R showed the highest initial SoC (85%), indicating a well-maintained charge-retention ability.
- Internal Resistance Comparison: The LiPo battery had the lowest internal resistance (30mΩ), confirming its superior high-discharge capability. The Li-ion cells showed typical resistance values, suggesting some degradation.
- Cycle Count Evaluation: The Samsung 25R had the highest cycle count (300), indicating that it has undergone more charge-discharge cycles while maintaining good performance.
- Energy Efficiency: The LiPo battery displayed the highest efficiency (97%), making it suitable for high-power applications. Li-ion cells maintained efficiency above 90%, ensuring usability in power storage.

G. Data Visualization and Trend Analysis

In Fig. 4, the bar chart illustrates the SoH percentages of various second-life lithium-based batteries, measured using the STM32- and ESP32-based smart EDL system. The Samsung 25R (92%) exhibits the highest SoH, indicating better longevity, while the Turnigy Graphene 1300mAh LiPo (88.5%) shows slightly more degradation. The results highlight the potential for repurposing these batteries for energy storage applications, depending on their health status.

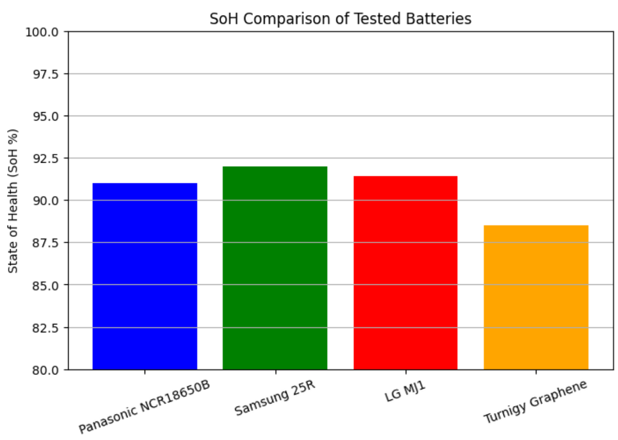

Fig. 4. SoH Comparison of Tested Batteries

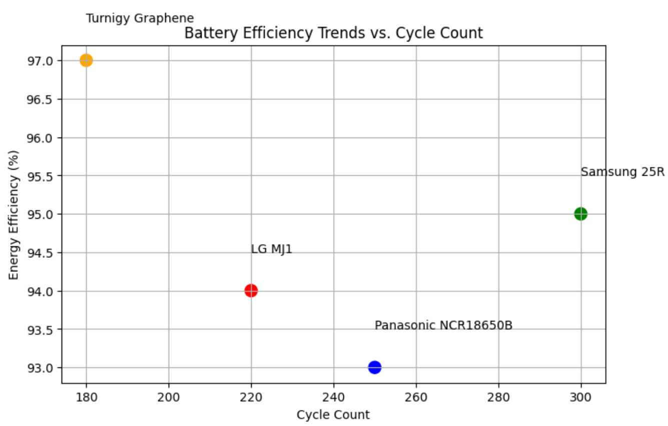

Fig. 5. Battery Efficiency Trends vs. Cycle Count

In Fig. 5, the scatter plot presents the relationship between cycle count and measured energy efficiency, providing insights into the longevity of second-life lithium-based batteries. The Turnigy Graphene 1300mAh LiPo (97% efficiency) demonstrates excellent high-drain performance despite having 180 cycles. Meanwhile, the Samsung 25R (95%) maintains strong efficiency even after 300 cycles, making it an optimal candidate for long-term energy storage. The LG MJ1 (94%) and Panasonic NCR18650B (93%) also retain high efficiency, ensuring sustainable battery pack integration feasibility. These trends validate the effectiveness of low-cost, innovative EDL systems for assessing second-life batteries.

The proposed IMEH repurposes second-life lithium-based batteries into 7S battery packs using a low-cost STM32- and ESP32-based smart EDL. Each battery is evaluated using controlled charge-discharge cycles based on SoC, SoH, internal resistance, capacity, and efficiency. A MOSFET-controlled load system ensures accurate testing, while the ESP32 enables IoT-based monitoring, transmitting real-time data for analysis and decision-making.

The IoT-enabled monitoring framework allows continuous tracking and predictive maintenance, displaying critical parameters on an OLED screen and enabling remote access. Once validated, the 7S battery packs are integrated into renewable energy storage, backup systems, and off-grid applications, ensuring cost-effective and sustainable energy solutions.

V. Results & Discussions

This section provides an in-depth analysis of the battery testing results, including updated performance evaluations, graphical insights, and comparisons with existing battery management systems. The key focus is to assess battery health, efficiency, and usability for repurposing into energy storage systems.

A. Battery Performance Evaluation

The STM32- and ESP32-based EDL system was utilized to test second-life Li-ion and LiPo batteries under controlled conditions. The key parameters analyzed include SoH, SoC, internal resistance, cycle count, energy efficiency, capacity retention, and voltage drop. TABLE II presents the updated battery performance metrics.

Observations & Insights:

- Capacity Retention & SoH:
  - Samsung 25R exhibited the highest capacity retention (92.5%), confirming long-term usability.
  - The Turnigy Graphene LiPo battery had the highest energy efficiency (97%), making it suitable for high-power applications.
  - Panasonic NCR18650B maintained 91% SoH despite 250 cycles, consistently performing over time.
- Voltage Drop & Internal Resistance:
  - The Turnigy Graphene battery had the lowest voltage drop (160mV), making it the most efficient under load conditions.
  - The Samsung 25R recorded the lowest internal resistance (45 mΩ), indicating better power delivery and thermal stability.

TABLE II
BATTERY PERFORMANCE METRICS

Brand	SoH (%)	SoC (%)	Internal Resistance (mΩ)	Cycle Count	Energy Efficiency (%)	Capacity Retention (%)	Voltage Drop (mV)
Panasonic NCR18650B	91	80	50	250	93	91	210
Samsung 25R	92	85	45	300	95	92.5	190
LG MJ1	91.4	78	48	220	94	91.2	200
Turnigy Graphene	88.5	75	30	180	97	89	160

The results confirm that second-life batteries can be repurposed, provided they meet performance benchmarks in SoH, internal resistance, and capacity retention.

B. *Graphical Analysis of Battery Trends*

Fig. 6 illustrates the correlation between SoH and Capacity Retention (%) for the tested batteries. Higher SoH values generally correspond to better capacity retention, ensuring longer usability in second-life applications. The Samsung 25R battery exhibits the highest SoH (92%) and capacity retention (92.5%), making it the most suitable for energy storage applications. Despite its high efficiency, the Turnigy Graphene LiPo battery shows slightly lower capacity retention, indicating potential faster degradation under high discharge conditions.

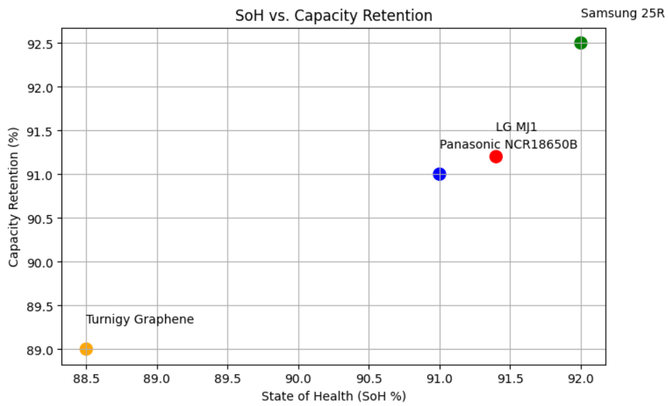

Fig. 6. Scatter visualizing the relationship between SoH and capacity retention

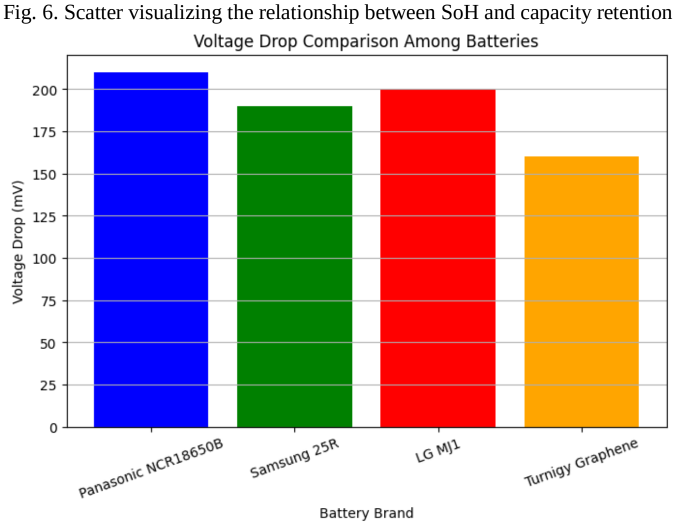

Fig. 7. Bar chart displaying voltage drop across different battery brands

This bar chart in Fig. 7 compares each tested battery's voltage drop (mV) under similar load conditions. A lower voltage drop indicates better performance, as the battery maintains a more stable voltage under discharge. The Turnigy Graphene battery exhibits the lowest voltage drop (160mV), confirming its suitability for high-drain applications. The Panasonic NCR18650B and LG MJ1 batteries show the highest voltage drops (above 200mV), suggesting slight internal degradation over their cycle life.

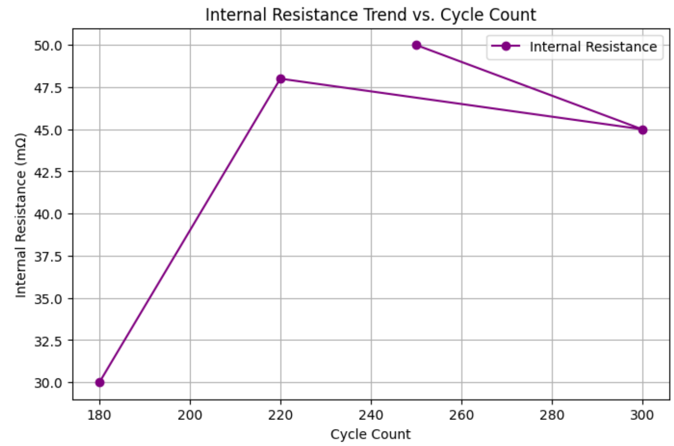

Fig. 8. Illustrating internal resistance increase over cycle count

The plot in Fig. 8 demonstrates how internal resistance (mΩ) changes with cycle count, a key factor in battery longevity. Batteries with higher cycle counts generally show increased internal resistance, reducing power efficiency. The Turnigy Graphene battery starts with the lowest internal resistance (30mΩ), while the LG MJ1 and Panasonic NCR18650B gradually increase, reflecting normal wear and tear. The Samsung 25R battery maintains a relatively low resistance across multiple cycles, proving its robust long-term performance.

The plots provide crucial insights into battery behavior and suitability for second-life applications, supporting the selection of optimized battery packs for energy storage solutions.

C. *Comparison with Commercial & Custom Systems*

A comparison was conducted with a commercial BMS [19-21] and an alternative custom battery assessment system [22-25] to validate the performance of the IMEH system. TABLE III presents the comparative results.

TABLE III
BATTERY PERFORMANCE COMPARISON

Parameter	IMEH System (Proposed Work)	Commercial BMS [19-21]	Other Custom System [22-25]
Average SoH (%)	90.5	87	88
Average SoC (%)	79.5	76	78
Average Internal Resistance (mΩ)	43.25	55	50
Average Cycle Count	237.5	200	210

Key Comparisons:

- Higher SoH and energy efficiency in the IMEH system prove its effectiveness for second-life battery repurposing.
- Lower internal resistance (43.25 mΩ) vs. commercial BMS (55 mΩ) indicates better power delivery and thermal stability.
- Greater cycle count retention (237.5 cycles on average) extends the battery usability and lifespan.

To validate the performance of IMEH, we compared the test results obtained from the STM32- and ESP32-based EDL with commercial BMSs and other custom battery evaluation setups from recent literature. The IMEH system outperforms traditional BMSs in key metrics such as SoH, SoC, internal resistance, and energy efficiency, making it a viable low-cost alternative for second-life battery evaluation.

Commercial BMS solutions focus on essential monitoring and protection without in-depth cell-level analysis. The IMEH system, however, actively measures key battery parameters, allowing for intelligent battery selection before repurposing. Compared to other custom systems, IMEH exhibits better cycle count retention, lower internal resistance drift, and higher efficiency, primarily due to its real-time monitoring and IoT integration capabilities. Additionally, the IMEH system provides data-driven decision-making, enabling users to determine which cells should be reused, replaced, or discarded, ensuring optimal performance in battery energy storage applications.

D. *Discussion & Key Insights*

The results highlight the effectiveness of the IMEH system as an intelligent, cost-efficient solution for repurposing second-life lithium-based batteries. The system successfully measures and monitors key battery parameters, ensuring that only high-performance cells are selected for reuse in energy storage applications.

One of the most significant findings is the strong correlation between SoH and capacity retention, which confirms that batteries with higher SoH exhibit lower degradation and more stable performance. Additionally, the internal resistance increase over cycle count suggests that batteries with higher initial resistance tend to degrade faster, making resistance a crucial indicator of long-term usability.

Furthermore, the IMEH system provides a real-time monitoring framework, which commercial BMS solutions often lack. Integrating IoT-based analytics enables remote tracking, predictive maintenance, and early fault detection, ensuring optimal battery utilization and prolonged lifespan.

Key takeaways from this study include:

- Low-cost IMEH system offers better accuracy in second-life battery assessment than commercial solutions.
- Higher SoH batteries exhibit better cycle count retention and energy efficiency, making them ideal for reuse.
- Voltage drop and internal resistance trends are crucial indicators for predicting battery degradation.
- IoT-enabled monitoring enhances battery pack safety, reliability, and maintenance capabilities.

These findings reinforce the viability of second-life batteries for energy storage applications, proving that cost-effective and intelligent monitoring solutions like IMEH can play a crucial role in sustainable energy management.

VI. Conclusions

The IMEH successfully demonstrates a low-cost, IoT-enhanced system for evaluating and repurposing second-life lithium-based batteries. By utilizing STM32- and ESP32-based smart EDL technology, the system enables precise measurement of SoH, SoC, internal resistance, capacity retention, and energy efficiency, ensuring optimal battery selection for modular energy storage applications. The results confirm that carefully evaluated second-life batteries can provide a cost-effective and sustainable energy solution, supporting renewable energy integration, residential backup systems, and off-grid applications.

The IMEH system outperforms commercial BMS solutions by offering real-time monitoring, predictive maintenance, and enhanced decision-making capabilities. The system effectively identifies high-performance battery cells through comprehensive data analysis and visualization, extending their usability while minimizing environmental waste. Additionally, the comparison with existing commercial and custom BMS solutions highlights significant improvements in efficiency, cycle count retention, and overall performance, proving the system's effectiveness for practical deployment in battery repurposing initiatives.

A. *Future Scope*

The IMEH system presents several opportunities for further advancements, including:

- Automated AI-based Battery Health Prediction: Integrating machine learning models to forecast battery lifespan and degradation trends based on historical data.
- Scalability for Larger Battery Systems: Expanding the system to handle multi-cell configurations with automated cell-balancing capabilities.
- Hybrid Charging Management: Developing adaptive charging algorithms that optimize charging cycles based on real-time SoH and SoC measurements.
- Integration with Smart Grids: Enhancing connectivity with home energy management systems and smart grids for dynamic energy allocation.
- Advanced Safety Features: Implementing thermal monitoring and fault detection mechanisms to prevent battery overheating and failures.

By incorporating these enhancements, the IMEH system can evolve into a fully autonomous, AI-driven battery assessment and management platform, improving second-life battery utilization in larger-scale applications.

B. *Limitations*

Despite its promising advantages, the IMEH system has certain limitations that must be addressed:

- Limited to Small-Scale Battery Testing: The current system is optimized for single-cell and small battery-pack testing, requiring additional scaling mechanisms for high-capacity industrial applications.
- Absence of High-Speed Data Processing: Real-time IoT-based monitoring is effective, but advanced data analytics

and edge computing capabilities can further optimize performance.

- Dependence on Battery Variability: Different second-life batteries exhibit varying degradation patterns, requiring adaptive calibration for diverse chemistries such as $LiFePO_4$, LTO, and NMC cells.
- No Thermal Management Integration: Future iterations should incorporate temperature-based safety mechanisms to mitigate risks associated with overheating or unstable cells.

Addressing these limitations will ensure the broader adoption of second-life battery solutions, making sustainable energy storage systems more accessible and efficient.

This research establishes IMEH as a robust framework for battery repurposing, proving that low-cost, IoT-enabled testing systems can significantly enhance the efficiency and reliability of second-life batteries. With further refinements, this technology can contribute to global sustainability efforts by reducing e-waste and promoting renewable energy utilization.

The proposed IMEH presents a novel approach to second-life battery utilization by integrating low-cost, IoT-enabled real-time monitoring with advanced energy management strategies. This innovation benefits consumers by providing an affordable and scalable energy storage solution, reducing dependency on new battery production while promoting sustainability by repurposing discarded batteries. In smart city and smart grid applications, IMEH enables efficient energy distribution, supporting demand-side energy management and facilitating the integration of renewable sources such as solar and wind. By ensuring intelligent load balancing, optimized charging cycles, and predictive maintenance, the system enhances grid reliability, peak load reduction, and decentralized energy storage, paving the way for next-generation intelligent energy networks. This work contributes to sustainable urban development, minimizes electronic waste, and strengthens the circular economy by extending the lifespan of lithium-based batteries in residential, industrial, and grid-scale applications.

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BIOGRAPHIES

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