Beyond Lithium-ion Battery Energy Storage Systems: Technology Testing and Evaluation at SCE

Arash Farokhi Soofi[1]
Farhad Elyasichamazkoti[1]
Arian Azizi[1]
Ahmadreza Momeni[1]
[1] Quanta Technology, LLC

Gabriel Andaya[2]
Ryan Miller[2]

[2]Southern California Edison (SCE)

Abstract— **The increasing need for grid flexibility and renewable integration has accelerated interest in advanced Battery Energy Storage Systems (BESS) that can deliver reliable, long-duration performance with improved safety and lifecycle characteristics. This paper presents the testbed design, implementation, and performance evaluation of the EnerVenue Nickel–Hydrogen (Ni–H_2) BESS deployed at Southern California Edison's (SCE) testing facility. The developed testbed integrates the Ni–H_2 BESS with a Dynapower MPS 125 inverter and supervisory control architecture to assess system-level efficiency and dynamic response. Comprehensive testing was conducted under multiple charge–discharge rates (C/2, C/4, and C/12) and during a 24-hour frequency regulation duty cycle, following the PNNL-22010 Rev. 1 protocol. Experimental results indicate round-trip energy efficiency of the battery increases more than 10% as the dis/charging rates decrease from C/2 to C/12. The battery exhibited stable voltage behavior, consistent response to high-power transients, and minimal degradation across operating regimes.**

***Index Terms*-- Nickel–Hydrogen Battery, Round-Trip Efficiency, Coulombic Efficiency, Voltaic Efficiency, Frequency Regulation Testbed.**

I. INTRODUCTION

The growing penetration of Distributed Energy Resources (DERs), such as wind and solar photovoltaics, presents a fundamental shift in the operation and planning of modern power systems. While these sources are essential for reducing greenhouse gas emissions, their volatility and limited dispatchability challenge the real-time balancing of supply and demand, frequency regulation, and overall grid reliability [1], [2].

Battery Energy Storage Systems (BESS) have emerged as a key enabler of flexibility in this evolving landscape. By rapidly storing and dispatching energy, BESS helps mitigate renewable variability, reduce curtailment, and enable greater renewable integration. Moreover, they provide a wide range of ancillary services such as frequency regulation, voltage support, and black start capabilities [3], [4]. At the distribution level, BESS can support peak shaving, load shifting, and defer costly infrastructure upgrades, contributing to both operational efficiency and economic optimization.

To make better planning and deployment decisions, it is essential to understand the landscape of available battery technologies, their underlying chemistries, and their performance trade-offs. Several types of batteries are currently in use or under development for power system applications, each with distinct characteristics in terms of energy density, efficiency, safety, cost, and lifecycle.

Several types of batteries are currently used or under development for power system applications, each with distinct performance characteristics. Lithium-ion (Li-ion) batteries, the most widely adopted, offer high energy and power density and high efficiency, but raise concerns about thermal safety and material supply chains, particularly for cobalt [5]. Lead-acid batteries are a mature and low-cost option with proven recyclability, yet suffer from low energy density and limited lifespan, making them suitable for backup applications [3]. Sodium-sulfur (NaS) batteries, operating at high temperatures, are efficient and energy-dense but require complex thermal management and pose safety risks due to molten sodium [6]. Lastly, flow batteries, such as vanadium redox flow batteries (VRFB), use liquid electrolytes to store energy and offer long lifespans, flexible scaling, and enhanced safety, though they tend to have lower energy density and higher upfront costs [4]. The diversity of these chemistries reflects the diversity of applications in the modern grid, and technology selection must align with specific operational needs, ranging from fast-response services to long-duration storage.

Among the less common but increasingly promising battery technologies, Nickel–Hydrogen (Ni–H_2) batteries have attracted renewed attention for large-scale energy storage applications beyond their traditional use in aerospace. Ni–H_2 batteries are distinguished by their exceptional cycle life, high reliability, and inherent safety characteristics, making them suitable for applications requiring long-term durability and minimal degradation. Recent advances in materials and system design have opened new possibilities for adapting Ni–H_2 chemistry to grid-scale storage by significantly reducing cost and improving volumetric efficiency [7]. However, a major barrier to the widespread commercialization of Ni–H_2 batteries

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remains the limited availability of testing data to validate their grid compatibility, operational safety, and real-world performance. This paper addresses this gap by evaluating the performance of a Nickel–Hydrogen Battery Energy Storage System (BESS) under realistic operating conditions, with the goal of accelerating the commercialization of next-generation, non–Li-ion battery technologies.

II. Testbed OverView

The developed testbed for evaluating the EnerVenue Nickel-Hydrogen BESS is presented in Fig. 1. Along with the EnerVenue Nickel-Hydrogen BESS (DC Block), a Dynapower MPS 125 inverter (AC Block), a SEL RTAC 3350 Site Controller (Control & Communications), and an HMI interface for real time monitoring and data acquisition are included in the testbed.

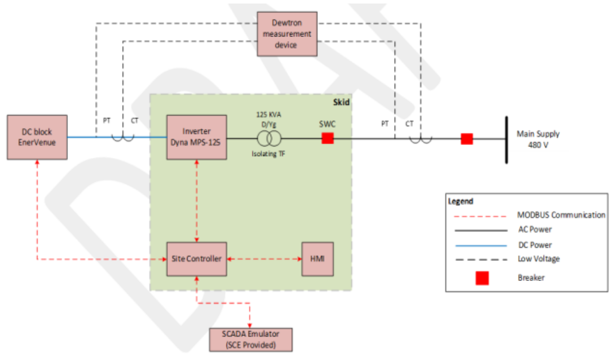

Figure 1. Oveall Testbed Overview.

EnerVenue Nickel-Hydrogen BESS and Dynapower MPS 125 inverter specifications are presented in Table I and Table II, respectively.

TABLE I. EnerVenue Nickel-Hyrogen Specifications

Characteristic	Value
Cell Voltage Range	6.75 - 9.8 Vdc
System Level Voltage Range	675 - 980 Vdc
Amp- Hour (DC Level – Single stack)	160 / 152 Ah
Type	Ni-H2

TABLE II. Dynapower MPS 125 Specifications

Characteristic	Value
Rated Output Real Power	125 kW
AC Voltage Rating	422-528 Vac
DC Voltage Rating	740 - 1475 Vdc
Response Time	<200 ms
Dimension (H x W x D)	36” x 27.75” x 15.25”
Weight	176 lbs

III. Test Procedure

The tests were performed to evaluate BESS performance during different C rates and use cases. The following use cases were performed:

- Round-Trip Efficiency Test
  - At C/2 rate (60 kW)
  - At C/4 rate (30 kW)
  - At C/12 rate (10 kW)
- Frequency Regulation Test.

A. Round-Trip Effiecincy Test

The purpose of this test is to determine the round-trip efficiency of the BESS. In addition to the BESS’s round-trip efficiency, the available energy capacity, and charge duration will also be extracted from the data generated while performing this test. The round-trip efficiency test shall be performed at the beginning of battery life, to extract the beginning of life characteristics for the test article. The round-trip efficiency test is conducted at C/2, C/4, and C/12 rates. The measured data, such as inverter DC power, BMS stack SoC, BMS maximum discharge power, and maximum and minimum cell voltages, are obtained from BMS, DC meter, and inverter.

B. Frequecny Regulation Test

The purpose of the frequency regulation test is to verify that the BESS can perform the PNNL frequency regulation duty cycle as specified in PNNL-22010 Rev. 1, Protocol for uniformly measuring and expressing the performance of energy storage systems. Fig. 2 shows a 24-hour normalized frequency regulation duty cycle. The maximum power will be scaled to the BESS’s maximum power (60 kW), and the BESS will be programmed to perform the scale duty cycle.

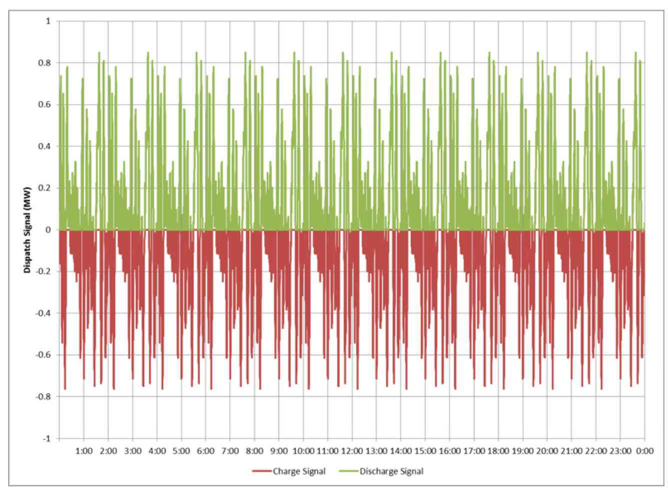

Figure 2. A 24-hour normalized frequency regulation duty cycle.

Measured data, such as inverter DC power, BMS stack SoC, BMS maximum discharge power, and maximum and minimum cell voltages, are obtained from BMS, DC meter, and inverter.

C. Key Performance Indicators

TABLE III. Key Performance Indicators (KPIs) for each test category are presented in Table III. These KPIs will be used to assess the performance of the BESS.KPIs for Each Test

Test Category	KPIs
Round Trip Efficiency Test	• Coulombic Efficiency Energy Efficiency • Voltaic Efficiency
Frequency Regulation Test	• SOC

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- Energy Efficiency

IV. Results & Discussion

In this section, results of round-trip efficiency and frequency regulation tests are presented, and key findings of each test are illustrated. It should be noted that these results are captured on the AC side of the battery, and they include the DC to AC conversion losses.

A. Round Trip Efficeincy Test Results

The power pack and battery cell data for round-trip efficiency of the BESS at C/12 rate are presented in Figs. 3 and 4.

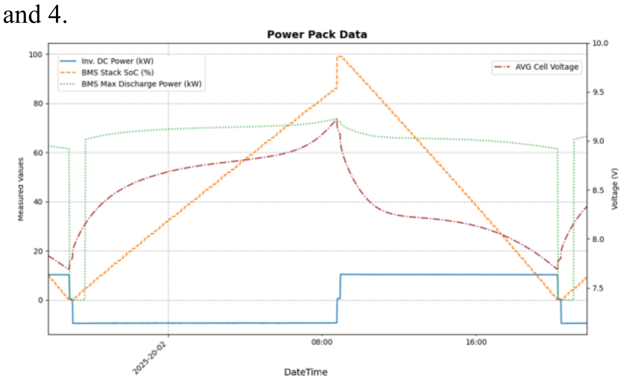

Figure 3. Power Pack Data of Round-Trip Efficiency at C/12 Rate.

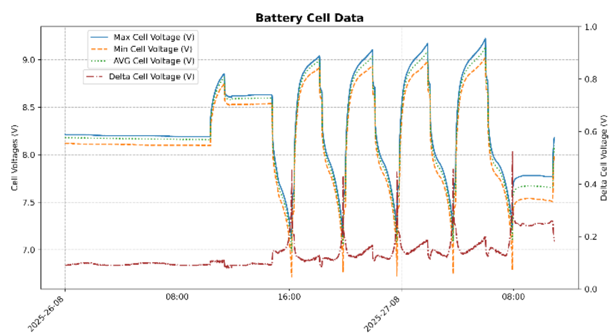

Figure 4. Battery Cell Data of Round-Trip Efficiency at C/12 Rate.

Besides, the power pack and battery cell data for round-trip efficiency of the BESS at C/4 rate are presented in Figs. 5 and 6. Based on Figs. 4 and 6, increasing the charging and discharging rate of the battery leads to more delta cell voltage.

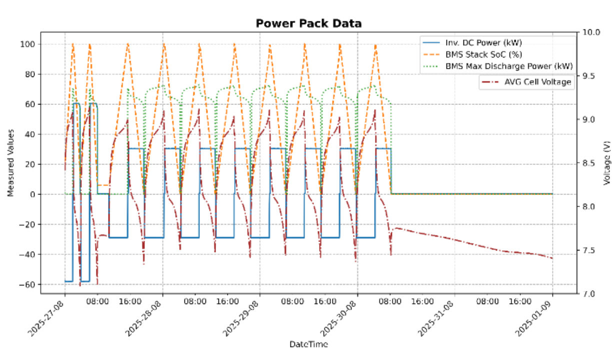

Figure 5. Power Pack Data of Round-Trip Efficiency at C/4 Rate.

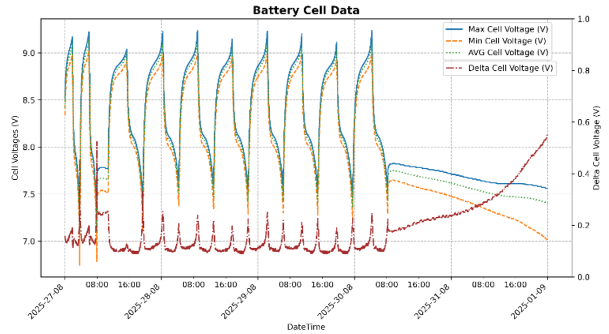

Figure 6. Battery Cell Data of Round-Trip Efficiency at C/4 Rate.

Moreover, the power pack and battery cell data for round-trip efficiency of the BESS at C/2 rate are presented in Figs. 7 and 8, respectively. Increasing the charging and discharging rate of the battery stack leads to more delta cell voltage as shown in Figs. 4, 6, and 8.

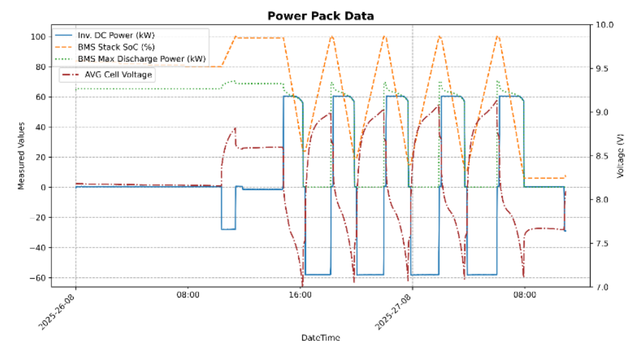

Figure 7. Power Pack Data of Round-Trip Efficiency at C/2 Rate.

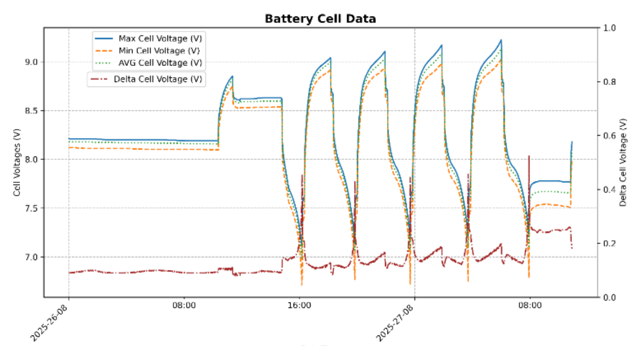

Figure 8. Battery Cell Data of Round-Trip Efficiency at C/2 Rate.

The measured charging and discharging energy of the BESS along with its calculated round trip efficiency are presented in Table IV. Table IV shows that the round-trip efficiency is increased as the chrging and discharging rates are decreased. The rount trip efficiency of the Enervenue battery is more than 10% when the charging and discharging rate of the battery increases from C/12 to C/2. During the testing procedure, it is observed that the RTE of the EnerEnue battery increases when the ambient temperature is decreased. The RTE of the battery at C/12, C/4, and C/2 rates procured at lower temperatures are 93.7%, 87.6%, and 83.2%, respectively.

TABLE IV. ENERGY AND ROUND-TRIP EFFICIENCY AT C/12, C/4, AND C/2 RATES

Parameter	C/12 Rate	C/4 Rate	C/2 Rate
Discharge Energy (kWh)	116.7	115.68	85.1
Charge Energy (kWh)	127.68	138.87	105.5
Round-Trip Efficiency (%)	91.22	83.3	80.7

The coulombic efficiency is calculated as the measured discharge capacity divided by the charge capacity as presented in Table V. Columbic efficiency has increased around 4% as the dis/charging rates decreased from C/2 to C/12.

TABLE V. CAPACITY AND COLUMBIC EFFICIENCY AT C/12, C/4, AND C/2 RATES

Parameter	C/12 Rate	C/4 Rate	C/2 Rate
Discharge Capacity (Ah)	142.59	144.57	139.6
Charge Capacity (Ah)	146.73	158.61	130.33
Coulombic Efficiency (%)	97.17	91.1	93.4

The average measured charge and discharge voltage of the BESS at C/4 and C/12 rates are presented in Table VI as well as the calculated voltaic efficiency. Calculated voltaic efficiency values shown in Table VI show that the higher dis/charging rates result in lowe voltaeic efficiency.

TABLE VI. VOLTAGE AND VOLTAIC EFFICIENCY AT C/12, C/4, AND C/2 RATES

Parameter	C/12 Rate	C/4 Rate	C/2 Rate
Average Discharge Voltage (V)	8.18	8.035	7.868
Average Charge Voltage (V)	8.68	8.762	8.881
Voltaic Efficiency (%)	94.26	91.7	88.6

B. Frequency Regulation Test Results

To test the BESS, four rounds of frequency regulation are performed as shown in Figs. 8 to Fig. 16. It should be noted that in all these tests, the BESS is charged 100% SoC then the frequency regulation tests are performed.

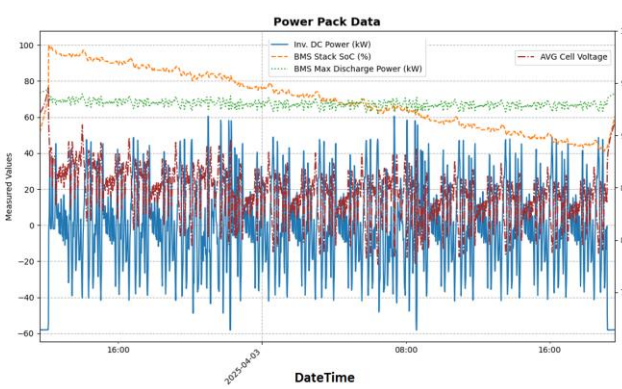

Figure 9. Power Pack Data of Frequency Regulation Test Round I.

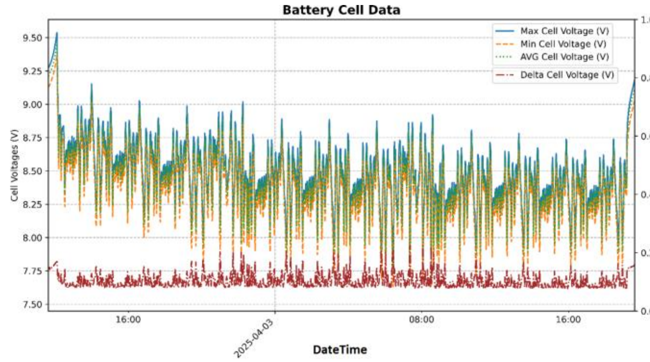

Figure 10. Battery Cell Data of Frequency Regulation Test Round I.

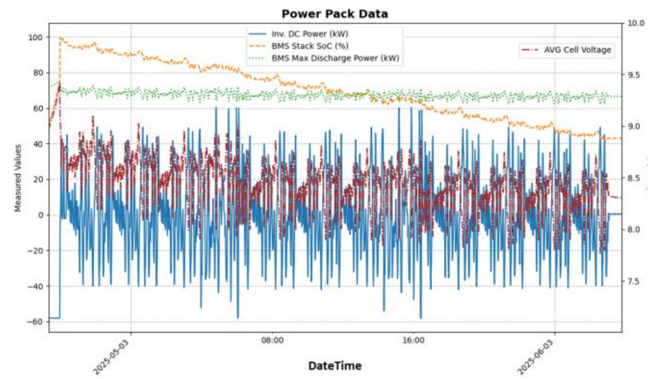

Figure 11. Power Pack Data of Frequency Regulation Test Round II.

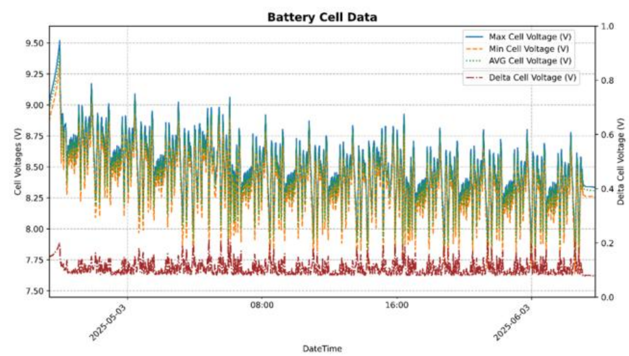

Figure 12. Battery Cell Data of Frequency Regulation Test Round II.

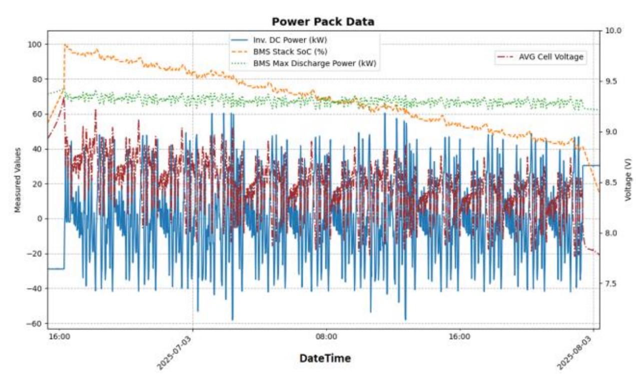

Figure 13. Power Pack Data of Frequency Regulation Test Round III.

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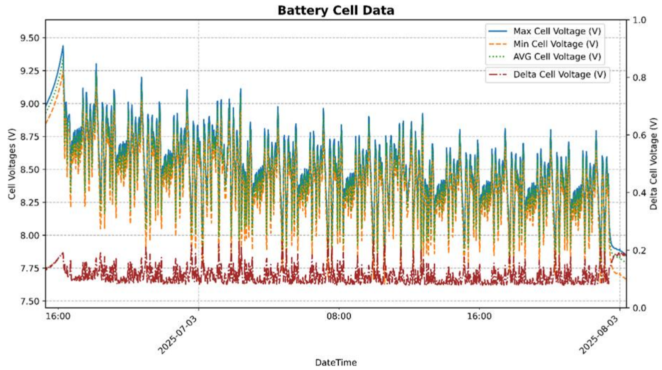

Figure 14. Battery Pack Data of Frequency Regulation Test Round III.

Table VII summarizes the frequency regulation tests results. Before performing the frequency regulation tests, the BMS stock SoC changes suddenly from values around 80% to 100%. During the frequency regulation tests, the BMS stock SoC decreases from 100% to around 40%. Net discharging energy of the BESS and its capacity are around 20% and 30% of their respective capabilities. During the tests, the average voltage reduces by 10% to 11% for all Rounds of the test.

TABLE VII. NET DISCHARGING ENERGY, NET DISCHARGING CAPACITY, AND AVERAGE VOLTAGE OF FREQUENCY REGULATION TESTS

Parameter	Round I	Round II	Round III
Net Discharging Energy (kWh)	22.97	22.79	23.48
Net Discharging Capacity (Ah)	46.22	46.33	48.27
Average Voltage (V)	8.42	8.42	8.44

After each round, the net charging energy and SoC are captured and summarized in Table VIII. The results show that for the SoC and charging energy are not aligned. Defining the error as expecting charging energy per SoC change, the error is 32.2%, 28.3%, and 15.6% for Round I to Round III of the tests, respectively. The main reason for these large errors is the SoC jumps from values around 80% to 100%. The error is larger for smaller SoC charge, due to the smaller charging energy.

TABLE VIII. NET CHARGING ENERGY, CHARGING RATE, AND SOC CHANGE AFTER FREQUENCY REGULATION TEST

Parameter	Round I	Round II	Round III
Net Charging Energy (kWh)	46.37	52.52	100.33
Charging C rate	C/2	C/4	C/4
SOC Change (%)	+57	+61	+99

V. CONCLUSIONS

A comprehensive testing process was conducted to characterize the performance of the EnerVenue Nickel–Hydrogen BESS at the Southern California Edison test facility. Through controlled round-trip efficiency and frequency regulation experiments, the results confirmed that the Ni–H_2 system delivers high operational stability, with efficiencies comparable to leading Li-ion technologies. The round-trip energy efficiency improved at lower C-rates, reaching 91.2% at C/12, while the coulombic and voltaic efficiencies also exceeded 90%, confirming low internal losses and high reversibility. During dynamic frequency regulation testing, the BESS demonstrated reliable tracking of grid-simulated signals and maintained voltage variation within 10–11%, validating its capability for ancillary service support. Observed discrepancies between state-of-charge changes and energy throughput highlighted areas for improved BMS calibration. Overall, the testing results affirm the Ni–H_2 BESS as a promising non–Li-ion alternative for long-duration, high-cycle, and safety-critical energy storage applications. Future work will include lifecycle aging tests, thermal performance characterization, and system-level optimization to support large-scale deployment and grid integration strategies.

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