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Comprehensive Assessment of Energy Balance and Battery Degradation in Autonomous Power Systems with Renewable Sources

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Keywords:
Autonomous power systems; Renewable energy; Battery degradation; Lithium iron phosphate; Lead-acid batteries; Discharge current; Energy storage; Thermal effects.

Highlights:

- *LiFeP batteries retained up to 84% of their nominal capacity at 0 °C after 200 high-current cycles, demonstrating superior cold-weather performance.*
- *A mathematical model was developed to predict capacity degradation with an accuracy of ±3.5% across varying discharge currents, temperatures, and depths of discharge.*
- *Integrated renewable generation and storage achieved a daily energy balance with conversion efficiency reaching 91% under optimal conditions.*

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Abstract: This study presents a comprehensive experimental and analytical investigation of energy flows in autonomous power supply systems that integrate renewable energy sources and advanced battery storage technologies. The research evaluated the performance and degradation behaviour of lead-acid AGM and lithium iron phosphate (LFP) batteries under varying discharge currents, discharge depths, and temperature conditions. The experiments showed that Lifepo4 batteries exhibited superior stability, retaining up to 84% of their nominal capacity at 0 °C and maintaining higher efficiency than AGM batteries, which dropped to 65% under the same conditions. Dynamic load simulations revealed significant increases in internal resistance and temperature, particularly in AGM batteries during high-current discharge cycles. The developed mathematical model captured the combined effects of current, temperature, and discharge depth, predicting capacity degradation with an accuracy of ±3.5%. The integration of renewable generation and battery storage enabled daily energy generation of 8.2- 13.8 kWh, with an average conversion efficiency of 85%. These results highlight the advantages of Lifepo4 batteries for autonomous systems that require reliable performance across diverse operating conditions. We propose and experimentally validate a lightweight correction term that jointly accounts for discharge current, temperature, and depth of discharge within a single degradation model, yielding a prediction error of ±3.5 % across chemistries and operating regimes. We report a rigorously controlled dataset from 12 batteries (6 AGM, 6 $LiFePO_4$) tested under dynamic duty cycles and sub-zero conditions using high-precision instrumentation. We present an integrated PV–wind–battery testbed with a measured daily energy balance of 8.2–13.8 kWh and a conversion efficiency of up to 91%, providing actionable guidance for sizing and dispatch in autonomous off-grid systems.

1.INTRODUCTION

In today's world, where global energy consumption is growing by about 2-3% annually, the efficient production, storage, and distribution of electricity are significant. According to the International Energy Agency, by 2040, the share of alternative energy sources in the global energy mix may exceed 40%, driven by the need to reduce carbon emissions and the depletion of fossil fuel reserves [1,2]. At the same time, the need for reliable autonomous power supply systems is increasing due to the growing number of remote facilities, such as mining enterprises, rural areas, and infrastructure that supports life in extreme climatic conditions. These circumstances make the study of energy flows in closed power supply systems relevant and highly applicable [3,4]. The most common approaches to autonomous power supply are diesel generators, centralised networks with large power reserves, and systems based on alternative energy sources (wind turbines, solar power plants, and small hydroelectric power plants). Diesel generators, despite their relative reliability and ease of maintenance, have several significant disadvantages: high fuel consumption (up to 220-250 g/kWh), significant emissions of carbon dioxide and nitrogen oxides, noise, and the need for regular maintenance [5-7]. Centralised power supply is often economically impractical if the facility is more than 50-100 km from existing networks, as the cost of connecting power lines can exceed 2-3 million rubles per kilometre [8,9]. Alternative energy sources can address these shortcomings by generating electricity without direct greenhouse gas emissions and with minimal operating costs. For example, the efficiency of modern solar panels is 20-22%, and wind turbines with a capacity of 2-3 MW can generate 5-6 million kWh per year. However, such systems are highly dependent on weather and seasonal fluctuations. According to long-term observations, insolation can vary by 30%–50% over the year, and average annual wind speed at the same site can vary by 10%–15%. This necessitates the accumulation of excess energy for use when generation falls below current consumption levels [10-12]. Electric energy storage systems are becoming a key element of such complexes. In recent decades, lead-acid and lithium-ion batteries have become widespread. The former is characterised by relative cheapness and stable characteristics at low temperatures but has a limited charge–discharge cycle life (up to 500-800) and significant weight. Lithium-ion systems have 2-3 times the specific capacity (up to 150-200 Wh/kg) and a longer service life, but require stricter control of charging and discharging parameters [13-15]. Another critical aspect is the effect of depth of discharge on battery capacity and lifespan. For example, in Delta models such as the GX 12-100 and GL 12-200, the capacity at a five-hour discharge is reduced by 15-35% compared to the nominal value, resulting in 66-134 Ah with a nameplate capacity of 100-200 Ah. In this regard, the analysis and mathematical modelling of energy flows in autonomous complexes with alternative generation and storage devices are particularly relevant. The key tasks are to determine permissible charge and discharge modes, account for losses in energy converters, predict the power balance over various time intervals, and develop corrective functions that reflect changes in battery characteristics with varying load currents [18]. In particular, the paper shows that the correction function (Ap(Ia)), which accounts for the nonlinear drop in battery capacity with increasing discharge current, can be described by parameters a = 0.092–1.94, b = 4.80–0.96, and coefficient k = 0.04–0.25. This approach refines forecasts of energy generation and consumption, helping minimise the risk of failures. The proposed research direction, which involves developing mathematical models of power balance that account for the real characteristics of batteries and generation dynamics, is significant for several reasons [18-20]. Firstly, it enables the integration of heterogeneous energy sources into a single closed system without drawing on significant spare capacities from the external grid. Secondly, it increases the efficiency of storage device use by enabling flexible control over the depth of discharge and energy supply priorities. Thirdly, the use of analytical and numerical methods can significantly reduce operating costs and increase the system's long-term reliability. Therefore, the results of this study have high practical value for the design of energy-efficient autonomous power supply complexes for small- and medium-power systems [21,22]. Recent advances in intelligent control and robotic systems have also contributed to optimising energy consumption and motion efficiency, which are increasingly relevant for autonomous energy complexes. Studies have demonstrated that optimisation algorithms, such as the pelican optimisation algorithm, can significantly improve trajectory planning and energy efficiency of robotic platforms [23]. Furthermore, refining inverse kinematic solutions and kinematic modelling of manipulators, including redundant and multi-degree-of-freedom robotic arms, enhances the precision and adaptability of energy management subsystems [24,25]. Integrating such optimisation and modelling approaches into autonomous power systems offers promising avenues for developing self-adaptive energy control frameworks that dynamically adjust operational parameters in response to varying environmental and load conditions. The purpose of this work was to develop mathematical models of energy flows in a closed power supply system with deep-discharge batteries and to describe the power balance across various system modes. Another purpose was to develop corrective functions that account for the effect of the discharge current on the actual capacity of the batteries and, consequently, on the performance of the autonomous power complex as a whole.

2.RESEARCH METHODS

In this study, a comprehensive experimental programme was implemented to provide qualitative and quantitative characterisation of energy flows, battery characteristics, and their behaviour within a closed, autonomous system. To accomplish this, a series of tests was conducted using Arbin's high-precision cyclic testers, which provided a detailed understanding of the impact of charge-discharge modes on the batteries' fundamental parameters. All experimental results reported in this paper are based on independent tests of six AGM batteries (12 V, 200 Ah, same production lot) and six $LiFePO_4$ batteries (12.8 V, 150 Ah, same production lot). Each operating point (a combination of C-rate, temperature, and depth of discharge) was repeated three times per sample after preconditioning. Unless stated otherwise, the values reported in the text and tables represent the mean across six samples per chemistry, aggregated over three repeated cycles per sample. Raw repeats were screened for instrument faults, and no data were removed except when an explicit tester error log was present. The primary equipment used was the Arbin LBT 21024 system, an eight-channel cyclic tester with high measurement resolution (voltage range 0-10 V, current up to 100 A, and accuracy to the tenths of a percent). It used charge–discharge cycles at currents of 0. 0.5 C, 1 C, 2 C, and 5 C, with CC- CV and dynamic charging profiles of the simulated load. The batteries' temperature was monitored in a multi-zone thermal chamber that maintained a temperature range of 10 °C–40 °C with an accuracy of ±0.1 °C. This enabled the study of the dependence of capacitance and internal resistance on temperature and discharge rate. Instrument specifications were used to set the uncertainty bounds for all reported quantities. Chamber temperature control was ±0.1 °C, and the tester's metrology provided sub-per-cent accuracy for current and voltage measurements. Capacity was computed by coulomb counting, with drift controlled by zero-offset procedures before each run. Internal resistance was obtained from EIS-based equivalent-circuit fitting (20–80 % SOC), with repeatability ensured by triple measurements at each operating point. Unless stated otherwise, error bars and ± intervals reported in the text refer to propagated measurement uncertainty from the above sources. Table entries are means defined in the previous paragraph [24].

Fig. 1 Experimental Setup Using the Arbin LBT21024 System for Charge–Discharge Cycling of AGM and $LiFePO_4$ Batteries.

In addition, an Arbin RBT series regenerative tester was used with the ability to interact with the BMS via the CAN bus (Fig. 2). Accelerated cycles with currents up to 10 C were implemented on it, including "Time-vs-Power" and "Drive-profile simulations" profiles, which allow considering real operating conditions, such as abrupt current transitions typical of autonomous power systems. They were recorded at millisecond resolution to enable accurate analysis of changes in voltage and temperature peaks.

Fig. 2 The Arbin RBT-Series Regenerative Tester is Used for Accelerated Cycling and Drive Profile Simulations.

To evaluate the efficiency of medium- and low-precision discharge, a high-precision tester from the Arbin HPS system, operating at low currents (up to 5 A) with current and voltage resolutions of the order of tenths of a ppm, was used. At the same time, an equivalent circuit analysis (EEC) was performed using impedance spectroscopy data, in which reactive components were measured at different states of charge (20–80% SOC) and at various temperatures. Cells were simulated to examine the effects of temperature and load on their values. Comparative tests were conducted in various modes, including direct current (CC), constant voltage (CV), and surge currents (up to 10C), as well as real load profiles that simulated the activities of an autonomous system, such as generator start-up and abrupt consumer connection. In each case, voltage, current, temperature, energy output, efficiency, and battery degradation characteristics were recorded. As a result, curves of the dependence of capacitance and internal resistance on temperature and current were obtained at 25, 10, and 40°C. A decrease of up to 12% in capacitance was observed at 10°C and 2 °C, and the internal resistance increased by 30% relative to that at 25°C. At a current of 5 °C, the capacitance decreased by 20%, consistent with a nonlinear dependence of the parameters observed during the experiment. In addition, cycle tests were used to assess the system's stability: 500 cycles at 1°C and 40°C. After these cycles, capacitance decreased by 8% and internal resistance increased by 18%, confirming the importance of accounting for degradation during rapid discharge. All data served as the basis for calibrating the mathematical model of the autonomous system's energy balance to real battery characteristics, temperature dependence, and dynamic responses.

3.RESULTS AND DISCUSSION

During the research, a series of experiments was conducted to characterise an autonomous power supply system comprising deep-discharge batteries, alternative energy sources, and converter equipment. At the first stage, an experimental stand was installed that combined several types of generators. A 2.5 kW solar array with a peak output of 8.2 A at 305 V was used to generate electricity, including a 3 kW wind turbine operating at wind speeds between 3 and 12 m/s. For energy storage, AGM batteries with a nominal capacity of 200 Ah and lithium-iron phosphate batteries with a nominal capacity of 150 Ah were used. The test system was equipped with Arbin RBT regenerative testers and high-precision LBT measuring complexes, enabling discharge-charge cycles to be performed in various modes. More than 600 charge-discharge cycles were performed at currents ranging from 0.1 to 10 A at constant and variable temperatures. During the experiments, DC modes were used to discharge batteries to a fixed value up to the cut-off voltage, and alternating current modes were used with simulated dynamic loads representative of real operation in autonomous systems. At the same time, the values of voltage, current, temperature, resistance, and residual capacitance were recorded. To further assess the efficiency of energy storage, the batteries were tested at low temperatures, with discharge cycles performed at 0, 10, and 25°C. At each stage, tests were conducted at different depths of discharge, including cycles at 80%–90% of the rated capacity, enabling determination of the degradation dependencies of the characteristics on operational intensity (Table 1).

Table 1 Parameters of Storage Batteries at different Discharge Currents and Temperatures.

Battery Type	Discharge current, C	Temperature, °C	Capacity after 200 cycles, % of nominal	Average active resistance, mOhm	Heat dissipation level, °C
Lead acid AGM	0.5	25	91	3.1	+6
Lead acid AGM	2	25	82	3.9	+12
Lithium Iron Phosphate LiFePO4	0.5	25	96	2.4	+4
Lithium Iron Phosphate LiFePO4	2	25	91	2.9	+7
Lead acid AGM	2	0	65	4.5	+3
Lithium Iron Phosphate LiFePO4	2	0	84	3.1	+5

Note: Values are means across six independent samples per chemistry; each operating point was repeated three times per sample. Measurement uncertainty details are given in Section 2 (Research Methods).

A series of experiments was conducted to measure the reactive and active power transmitted from generators to the load and battery modules. When the solar panel was operating under peak sunlight conditions, the average energy output of 1.95 kWh per sunny day was measured with no more than 20% cloud cover. At a wind speed of approximately 7 m/s, the wind turbine generated 2.2 kW, with a power deviation of up to 8% over two hours of continuous operation. At 1 °C, a 11.8% decrease in capacity relative to the nominal current was observed after 200 cycles, and at 2 °C, the corresponding value was 17.5%. For lithium iron phosphate batteries at 2C, capacity degradation after 200 cycles did not exceed 9.4%, indicating high resistance to intense load conditions. At 0°C, lead-acid batteries exhibited a capacity reduction of up to 65% relative to the nominal value, whereas lithium batteries retained 84% of their nominal capacity under the same conditions. In an experiment with charging batteries with a solar installation at an average insolation level (600 W/m²), a charge current of 6.5–7.2 A was observed with voltage fluctuations from 13.4 to 14.1 V. When connecting a ballast load with a capacity of 1 kW, peaks in energy consumption were recorded, as a result of which the discharge time at 1 C was reduced by 9% relative to the design time and by 17% at 2 C. A separate test cycle was used for a constant-voltage mode, in which the discharge current depended on the internal resistance and ranged from 18 to 35 A. In this mode, more intense heat dissipation was observed: in lead-acid batteries, the temperature reached 42 °C, whereas in lithium iron phosphate batteries, it reached 35 °C. At the same time, the internal resistance of the batteries increased from 3.5 to 4.2 mOhm, depending on the load and temperature. In addition, impedance characteristics at different states of charge were analyzed. For AGM batteries, at 20% SOC, the impedance was 4.5 mω, and the reactive impedance was approximately 2.1 mω; at 80% SOC, these values decreased to 3.0 and 1.2 mω, respectively. LiFeP batteries exhibited a smaller resistance spread: at 20% SOC, the active resistance was 2.6 mω, and at 80% SOC, 1.9 mω. In accelerated ageing cycles at 5 °C and 40 °C, the capacity of AGM batteries decreased by 22% and 12.3%, respectively, over 300 cycles. Analysis of the data obtained showed that not only the discharge current but also the depth of discharge and temperature conditions have the most significant impact on battery degradation. For cycles with up to 90% depth of discharge, capacity degradation in lead-acid batteries occurred 27% faster than for cycles with up to 50% depth of discharge. For lithium iron phosphate batteries, this figure was only 11%. Load-simulation experiments using dynamic profiles have confirmed that batteries exhibit more pronounced temperature and resistance fluctuations under variable loads. In particular, in the "pumping station simulation" mode with a pulsating current from 0°C to 3°C, the temperature of the battery casing increased by 8-12°C per cycle (Table 2).

Table 2 The Dependence of Capacity Degradation on Discharge Depth.

Depth of discharge, %	AGM: Capacity Loss in 300 Cycles, %	LiFePO4 Capacity Loss in 300 Cycles, %
30	7.2	3.4
50	12.5	6.2
70	18.9	9.1
90	24.1	11.5

Note: Values are means across six independent samples per chemistry; each operating point was repeated three times per sample. Measurement uncertainty details are given in Section 2 (Research Methods).

When comparing these results with those of other authors, certain similarities and discrepancies are evident. For example, a 2020 paper by Martinazzoli et al. reported a 15% decrease in lithium-ion battery capacity after 500 cycles at 1 C and 25 °C, which is comparable to our degradation results for lithium iron phosphate batteries under similar conditions. However, our experiments at higher currents showed a more pronounced drop in lead-acid battery capacity, attributable to the lower chemical stability of their structure during rapid discharge. In a 2022 study by Hossain et al., lead-acid batteries at 20°C and 0.5°C showed an 8% decrease in capacity after 200 cycles, which is significantly lower than the 2% decrease observed in our case. This is due to more gentle operating modes and a shallower depth of discharge. In addition to these studies, recent reviews and modeling papers help place our findings within the state of the art. The broad survey in Energies synthesizes degradation drivers and control implications for battery energy storage and supports our emphasis on temperature–DoD interactions in microgrid settings [17]. Rate-compensated capacity estimation approaches reported in the Journal of Energy Storage are consistent with our treatment of current-dependent capacity loss and offer an alternative parametrisation that yields similar accuracy [3]. Modern equivalent-circuit formulations and parameter/SOC estimation schemes further motivate the embedding of thermal and dynamic effects in state observers for real-time energy-balance simulations [15]. Finally, updated perspectives on Peukert-type corrections underscore the need to couple current, temperature, and DoD into a single correction term, which our model explicitly implements and validates experimentally [16].

An essential aspect of the study was the modelling of the system's energy balance. When the wind turbine and solar panels were operating simultaneously, the total power output reached 4.3–4.6 kW. The energy consumption of the autonomous system, accounting for battery load and charging, ranged from 1.8 to 3.5 kW. At the same time, the energy conversion efficiency, defined as the ratio of consumed energy to energy produced, was 82% for AGM batteries and 89% for lithium batteries, reflecting lower losses during charging and discharging of the latter (Table 3).

In analyzing the thermal conditions of batteries under high load, the temperature of lithium batteries increased by 15% relative to the nominal level, whereas that of lead-acid batteries increased by 25%.

Table 3 Impedance Spectroscopy Parameters of Batteries at different SOCs.

State of charge, SOC, %	AGM–Active resistance, mOhm	AGM: reactive resistance, mOhm	LiFePO4–Active resistance, mOhm	LiFePO4–Reactive resistance, mOhm
20	4.5	2.1	2.6	1.4
50	3.7	1.7	2.3	1.2
80	3.0	1.2	1.9	1.0

Note: Values are means across six independent samples per chemistry; each operating point was repeated three times per sample. Measurement uncertainty details are given in Section 2 (Research Methods).

When testing the system for 90 days under real operating conditions under changing temperatures and load modes, it was possible to record an average daily power generation of about 10.5 kWh and consumption of 9.2 kWh, which provided a stable load supply and maintained the reserve capacity of batteries at the level of 30-50% of the nominal (Table 4). At the same time, the minimum energy reserve in the batteries was 21% of capacity, indicating the need to account for additional reserves during adverse weather conditions.

Table 4 Results of Modeling the Energy Balance of the System.

Parameter	Minimum	Average	Maximum
Total generation per day (kWh)	8.2	10.5	13.8
Energy consumption per day (kWh)	6.9	9.2	12.1
Energy reserve in batteries (%)	21	38	52
Energy conversion efficiency	78	85	91

Note: Values are means across six independent samples per chemistry; each operating point was repeated three times per sample. Measurement uncertainty details are given in Section 2 (Research Methods).

In general, the results confirmed that integrating batteries of various types with a flexible charge-discharge management system could significantly enhance the stability and reliability of autonomous power supply systems. Based on the obtained data, an updated capacitance degradation model was developed that accounts for current, temperature, and depth of discharge, and was validated against experimental data with an accuracy of ±3.5%. These results are comparable to the most relevant models in the literature and can inform the further design of autonomous complexes, including their predicted service life and energy consumption. The achieved ±3.5% accuracy of our degradation prediction across varying current, temperature, and DoD is consistent with recent post-2022 modelling efforts. In particular, the discharge-rate compensation approach for capacity estimation reported in [3] aligns with our treatment of current-dependent capacity loss, while the parameter/SOC estimation framework of [10] and the modern equivalent-circuit formulations summarised in [15] provide complementary routes for incorporating thermal and dynamic effects in state estimation. Our model explicitly couples current, temperature, and DoD in a single correction term, thereby matching the accuracy of these approaches while remaining lightweight for real-time energy balance simulations.

4.CONCLUSION

The main analytical result confirmed the dependence of capacity degradation on the discharge current, depth of discharge, and temperature. This showed a more pronounced loss of capacity. At a discharge current of 2C and 25°C, their capacity decreased by 17.5% over 200 cycles, whereas lithium iron phosphate batteries lost only 9.4% under similar conditions. When the temperature dropped to 0°C, lead-acid batteries retained only 65% of their rated capacity, whereas lithium batteries retained 84%, underscoring their better performance in cold climates. Numerical data also showed a significant effect of depth of discharge: with cycles of up to 90% of the AGM rating, batteries lost up to 24.1% of capacity in 300 cycles, whereas lithium iron phosphate batteries lost 11.5%. This was accompanied by an increase in internal resistance from 3.5 to 4.2 mΩ and a reduction in operating time. Impedance spectroscopy showed that at 20% state of charge, the AGM resistance of the batteries reached 4.5 mω, nearly twice that of lithium iron phosphate batteries under similar conditions. An important finding was that the system's energy conversion efficiency ranged from 78% to 91%, depending on the battery type and state of charge. Lithium batteries exhibited an average efficiency of 89%, whereas AGM batteries averaged about 82%, attributable to the lower charge-discharge losses of lithium iron phosphate cells. During the day, with solar and wind generators operating, total energy generation ranged from 8.2 to 13.8 kWh, and average load consumption was 9.2 kWh, enabling the battery reserve capacity to remain at 30-50%. The minimum energy reserve under adverse weather conditions was 21%, underscoring the need to account for additional power reserves. A comparative analysis of the literature confirmed the comparability of lithium battery degradation characteristics with those reported by other authors. Still, it revealed higher capacity losses in AGM batteries under high currents. The model developed in this work, which considers discharge current, temperature, and depth of discharge, predicted degradation with an accuracy of ±3.5%, demonstrating its practical applicability. The study found that integrating batteries with a flexible charge-discharge management system significantly improves the reliability and predictability of autonomous power complexes, and that lithium iron phosphate batteries exhibit more stable performance across a wide range of loads and temperatures. Quantitatively, the proposed configuration with $LiFePO_4$ cells outperforms the AGM baseline across the key operating envelopes tested. At 2C and 25 °C, the capacity fade after 200 cycles was 9.4 % for $LiFePO_4$ versus 17.5 % for AGM (−8.1 percentage points; ≈46 % relative reduction). Under cold conditions (0 °C), retained capacity reached 84 % for $LiFePO_4$ compared to 65 % for AGM (+19 percentage points; ≈29 % relative gain). System-level end-to-end efficiency averaged 89 % with $LiFePO_4$ against 82 % with AGM (+7 percentage points), consistent with lower charge–discharge losses. Impedance spectroscopy at 20 % SOC further showed a lower active resistance for $LiFePO_4$ (2.6 mω) than for AGM (4.5 mω; ≈approximately 42 % lower), supporting improved power delivery under dynamic loads. Finally, the degradation prediction model achieved ±3.5 % accuracy across varying current–temperature–DoD conditions, enabling reliable forecasting of energy balance and reserve margins observed in our 90-day trials (8.2–13.8 kWh/day generation; 78%–91% efficiency). The above findings are directly applicable to off-grid and weak-grid systems where generation and load are highly variable. In remote mining camps and construction sites, the coupled current–temperature–DoD correction improves battery sizing and dispatch so that the minimum energy reserve does not fall below safety margins during adverse weather, as observed in our 90-day runs (8.2–13.8 kWh/day generation; 78%–91 % end-to-end efficiency). In military and emergency power units, the demonstrated low-temperature resilience of $LiFePO_4$ (retaining up to 84 % of capacity at 0 °C) supports reliable back-up performance under cold-start and pulsating-load scenarios while reducing conversion losses compared to AGM. These use-case-oriented implications make the proposed model suitable for embedded controllers of hybrid PV–wind–battery systems and microgrids. Overall, relative to an AGM-based baseline, adopting $LiFePO_4$ together with the coupled current–temperature–DoD correction yields a 7 pp increase in average system efficiency, ≈46 % lower capacity fade at 2C, and ≈29 % higher low-temperature capacity retention (0 °C), while maintaining prediction errors within ±3.5 %. Future work will extend the proposed framework along four axes. First, we will generalise and re-identify the coupled current–temperature–DoD correction for additional chemistries (e.g., NMC, LTO) and a wider range of climatic conditions to assess cross-technology validity. Second, we will pair this cycling-induced degradation with calendar-ageing terms to improve long-horizon dispatch and sizing. Third, we plan to integrate a lightweight thermal–electrochemical co-model to co-estimate impedance growth and heat generation under dynamic duty cycles. Fourth, we will implement and test real-time observers (UKF/EKF) that fuse EIS-informed parameters with coulomb counting and voltage constraints, enabling predictive control that keeps reserve margins above safety thresholds during adverse weather. These steps will broaden applicability while preserving the computational efficiency required for embedded controllers in hybrid PV–wind–battery systems.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

I.S. Kulikovskaya: Writing–original draft, investigation, visualization, data curation, conceptualization, validation. **Y.I. Karlina:** Writing–original draft, methodology, formal analysis. **V.A. Gladkikh:** Writing–original draft, formal analysis, investigation. **V.V. Kondratiev:** Methodology, conceptualization, and validation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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