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Framework for Battery Energy Storage System Bridging Technical Performance and Financial Viability

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Abstract

Battery Energy Storage Systems (BESS) are a new key to modernizing power grids, supporting renewable integration, improving grid flexibility, and supporting distributed energy resources. This paper proposes a unified framework that integrates analytics, system design, and economic modeling to guide scalable, data-driven BESS deployment. A modular Python-based dashboard links technical performance, mainly state of charge dynamics, tracks degradation through remaining capacity trends, monitors budget utilization, maps hourly load demand patterns, and compares energy density and cost across battery chemistries. Financial indicators levelized cost of storage, net present value, and internal rate of return, are linked to technical key performance indicators, enabling stakeholders to simulate, monitor, and optimize operational and financial outcomes. The framework is validated on a 1 MW/2 MWh lithium ferrophosphate-based BESS, demonstrating high operational efficiency, robust financial returns, and long-term sustainability. This integrated perspective bridges the gap between engineering reliability and commercial bankability, providing a scalable blueprint for utility-scale and distributed energy storage projects.

Keywords

Battery Energy Storage System (BESS); Techno-economic analysis, Financial viability; Energy storage framework

1. Introduction

Renewable energy is being integrated into global power systems at an accelerating rate, and while solar and wind generation are key drivers of decarbonisation, their inherent variability presents challenges to grid reliability. Battery energy storage systems (BESS) have emerged as a promising solution to this challenge, enabling energy balancing, frequency regulation, and peak shaving while facilitating deeper renewable energy penetration [1]. In addition to grid stabilisation, BESS plays a pivotal role in empowering distributed energy resources (DERs), microgrids, and virtual power plants (VPPs). As a result, consumers are transformed into prosumers, and market participation in modern electricity systems is reshaped [2]. Despite such assurances, the large-scale deployment of BESS continues to face a persistent disconnect between technical performance and financial viability. Technical experts focus on metrics such as state of charge (SoC), round-trip efficiency, and degradation profiles, whereas investors prioritise financial indicators such as levelised cost of storage (LCOS), net present value (NPV), and internal rate of return (IRR) [3]. These perspectives rarely converge, resulting in deployments where operational realities undermine financial expectations, or where financially modelled projects fail to reflect technical complexities such as cycle degradation, volatile raw material costs, or thermal management constraints [4]. Lithium Iron Phosphate (LFP) and Sodium Ion Batteries (NIB) batteries have become the chemistry of choice for utility-scale applications, offering thermal stability, long cycle life, and favorable safety characteristics [5]. However, challenges persist—including

non-linear degradation under dynamic load conditions, limited recycling infrastructure, and revenue uncertainty due to fluctuating ancillary market prices. Moreover, the technical complexity of modern BESS, including advanced bidirectional power converters that comply with evolving grid codes (e.g., IEEE 1547) and predictive energy management systems (EMS), adds an extra dimension to lifecycle financial modelling [6].

A critical gap in the industry is the lack of integrated frameworks capable of simultaneously tracking technical KPIs and projecting financial outcomes in real-time solutions. Existing tools often operate in isolation, forcing stakeholders to make fragmented decisions based on incomplete data. The result is suboptimal asset utilization, premature degradation, missed revenue opportunities, and an underestimation of long-term value. This study addresses these challenges by proposing a unified, modular framework that bridges engineering rigor with financial pragmatism. The framework consolidates real-time operational data, such as SoC dynamics, capacity fade trends, thermal management efficiency, and load profiles, with predictive financial modeling that considers lifecycle costs, revenue streams, and investment returns. This approach is centred around a Python-based analytics dashboard that is intended to provide actionable insights for operators, engineers, and financiers. Validated on a 1 MW/2 MWh LFP-based BESS, the framework demonstrates how integrated analytics can extend asset life, optimize operational strategies, and ensure robust financial returns. By analysing the traditional separation between technical design and economic modelling, this work provides a scalable, replicable model for the deployment of BESS that are not only technically superior but also commercially bankable. This is an essential step as energy storage transitions from a technical adjunct to a core pillar of the modern energy economy.

2. System Design and Development

The primary objective is to develop an integrated digital environment that links system design, operational analytics, and economic modeling, providing stakeholders with actionable insights for both predeployment planning and operational optimization. Battery Energy Storage Systems (BESS) operate through a multilayered control architecture [7] as shown in Figure 1, comprising the Supervisory Control and Data Acquisition (SCADA) system, the Energy Management System (EMS), and the Battery Management System (BMS). SCADA facilitates grid-level integration and ensures regulatory compliance, EMS oversees application-level energy dispatch for functions such as peak shaving and load shifting, while BMS is responsible for monitoring internal battery parameters, including voltage, temperature, and State of Charge (SoC). Although each subsystem generates valuable operational data, these outputs often exist in isolation, limiting the potential for cross-layer optimization. The degradation trends identified by the BMS are seldom integrated into EMS strategies aimed at maximizing revenue or extending battery lifespan.

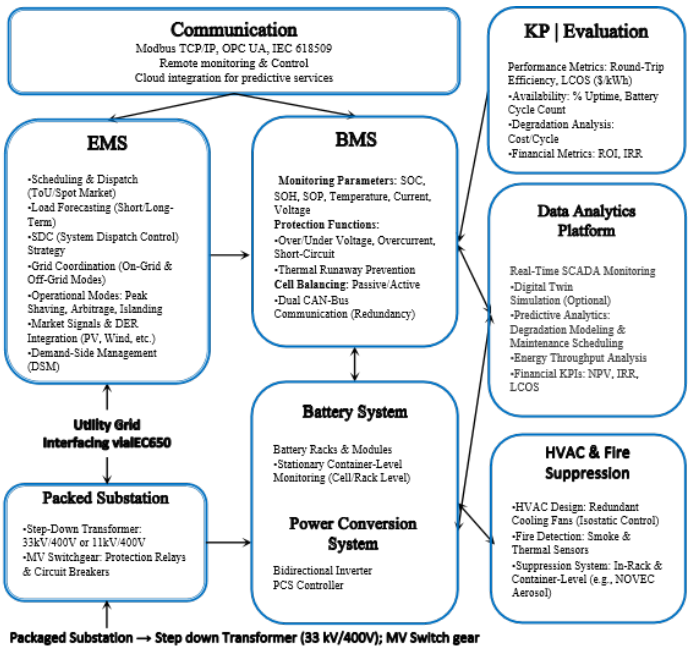

Figure 1. System Architecture and Grid Integration of the Battery Systems. The blue-colored boxes highlight the key operational segments that are visualized and monitored through the integrated dashboard.

At the core of the BESS design and development of a 1 MW/2 MWh system lies a modular and scalable architecture, engineered for phased deployment, flexible augmentation, and streamlined maintenance. Modular battery racks, each providing 100-200 kWh capacity, facilitate redundancy and enable selective replacement, thus minimizing downtime during maintenance cycles. Conventional containerized battery energy storage system (BESS) deployments typically achieve an energy capacity on the order of ~500 kWh per standard 20-foot equivalent unit (TEU), with configurations designed to accommodate heterogeneous or hybrid chemistries at the system level [8]. Recent advancements by CATL, however, have demonstrated a substantial increase in volumetric energy density, achieving approximately 6,250 kWh within a comparable 20-foot container footprint [9]. Notably, the overall system footprint remains below 50 m², rendering it well-suited for urban and space-constrained installations. The Power Conversion System (PCS) is configured for bidirectional power flow with ≥96% round-trip efficiency and full compliance with IEEE 1547 and UL 9540 standards. Wide input voltage compatibility ensures adaptability to multiple battery chemistries, supporting long-term technology evolution. Grid interfacing is achieved via integration with a 480VAC±10% nominal, 60Hz distribution panel (IEEE 1547-2018 and UL 1741SB), with total harmonic distortion (THD) maintained below 5% through active harmonic filtering. Medium voltage interconnection is supported by vacuum circuit breakers and 12.47 kV substations, ensuring robust coupling with utility infrastructure.

The system utilizes Lithium Iron Phosphate (LFP) chemistry, delivering 4,000-6,000 cycles at 80% DoD with an energy density of 150-170 Wh/kg (±10% variance across lifecycle) at the cell level. LFP offers the optimal balance of thermal stability, cycle life, and safety for stationary grid-scale applications [8]. While alternatives like Nickel Manganese Cobalt (NMC) provide higher energy density, LFP's lower thermal runaway risk makes it the preferred choice for utility-scale deployments. Emerging chemistries such as sodium-ion and second-life lithium-ion show potential for cost or sustainability-driven use cases but remain limited by lifecycle maturity and commercial readiness. Maximizing asset life and financial predictability requires integrated lifecycle management strategies. Battery Management System (BMS) for providing granular data on State of Charge (SoC), State of Health (SoH), thermal conditions, and impedance variations. Supervisory Control and Data Acquisition (SCADA) for capturing system-level operational parameters and grid interface dynamics [10]. With market Apps in delivering up-to-date electricity pricing, ancillary service tariffs, and future revenue forecasts. At the core of the system is an advanced Optimization Engine powered by Model Predictive Control (MPC). Acting as the framework's decision-making brain, MPC forecasts future states based on telemetry inputs, operational constraints, and market signals. Thermal management is pivotal to system safety and longevity. Liquid cooling maintains uniform cell temperatures within ±2°C across a 25–35°C range, eliminating hotspots [11]. Fire suppression systems combine aerosol agents with solid-state breakers and high-speed fuses for rapid fault mitigation. Thermal runaway propagation barriers (TRPBs) embedded at the module level further prevent cascading failures. Advanced EMS algorithms employ model predictive control (MPC) to optimize grid services—including peak shaving, frequency regulation, and renewable energy firming—balancing technical longevity with financial returns. Tight EMS–BMS integration ensures real-time coordination of dispatch with thermal, degradation, and revenue models. The BMS maintains precise cell voltage balancing (±10 mV) and >98% SoH estimation accuracy [12], supporting predictive maintenance routines. The PCS architecture accommodates evolving battery technologies with multi-chemistry voltage compatibility—LFP (2.5-3.6V), NMC (3.0-4.2V), and Na-ion (2.0-3.7V), enabling future adaptation without major infrastructure modifications [8].

Structural reinforcements with seismic anchoring and wind-load mitigation are incorporated to meet regional building codes and environmental resilience requirements. The system offers ≥10 years of service life with ≥70% capacity retention and >99% availability, forming the foundation of its investment-grade proposition for commercial stakeholders [13]. Full compliance with UL 9540, IEC 62619, IEC 62933, and UN 38.3 ensures safety, transport viability, and grid interoperability [14]. These standards comprehensively address fire mitigation, electrical protection, and integration with utility infrastructure. Envision and CLOU Electronics [15] have conducted extended fire propagation tests exceeding 59 hours at temperatures surpassing 1,300 °C, thereby surpassing typical UL 9540A testing requirements. These enhanced testing protocols effectively raise the benchmark for safety performance, potentially setting new expectations for insurers and regulatory bodies. Moreover, it is anticipated that UL 9540A and CSA C800 may converge into a more stringent unified testing standard in the near future. Cybersecurity measures adhere to IEC 62351, protecting against cyber threats, especially in grid-edge and remotely monitored deployments. A hierarchical control stack underpins system integration, providing structured coordination across device, site, and fleet levels.

One of the core ideas of the framework is its use of a virtual prototyping platform embedded within a Python-based dashboard. Designed to bridge the disconnect between technical performance metrics and financial decision-making in Battery Energy Storage Systems (BESS). Existing platforms (Cell-Level Firmware, Module Middleware,

System Algorithms) that attempt to unify these layers remain largely retrospective, fragmented, and non-dynamic. Technical diagnostics and operational monitoring State of Charge (SoC) dynamics, Capacity degradation and lifecycle trends, Load demand profiling and forecasting, benchmarking of technology costs across battery chemistries, while financial tools like Excel and Tableau are used to evaluate economic metrics such as Capital and operational expenditure tracking (CapEx/OpEx), Levelized Cost of Storage (LCOS) evaluation, Revenue aggregation from grid services and market participation. This bifurcation prevents holistic analysis, such as understanding how aggressive charge/discharge patterns simultaneously influence battery degradation and financial returns.

3. Technical Performance Analytics

The proposed analytics dashboard functions as the central visualization and decision-support interface for the unified BESS framework, delivering real-time, predictive, and financial intelligence to stakeholders across technical, operational, and financial domains. The framework is designed around a modular, customizable architecture, enabling scenario-specific analyses for a broad spectrum of stakeholders, including engineers, system designers, financial analysts, and asset managers.

At the core of the dashboard is the Battery analytics module, offering continuous visualization of State of Charge (SoC) dynamics across diverse load profiles. By aligning these patterns with load shifting, peak shaving, and predictive charging strategies managed by the Energy Management System (EMS), stakeholders can directly correlate operational flexibility with financial outcomes. Complementing this, the Remaining Capacity Trend plots track capacity fade over time, enabling proactive scheduling of maintenance and replacements while supporting compliance with OEM warranty constraints.

Thermal safety is addressed through the Thermal Risk Insights module, which integrates real-time telemetry from the Battery Management System (BMS) with predictive thermal simulations. By overlaying hotspot maps and thermal runaway risk bands, the system facilitates preemptive interventions, safeguarding battery integrity during high-stress operational periods. To link technical operation with grid interaction, Load Demand Behavior heatmaps present hourly and seasonal demand fluctuations, optimizing both peak shaving and arbitrage strategies. These visualizations align with operational priorities in commercial, industrial, and grid-support contexts.

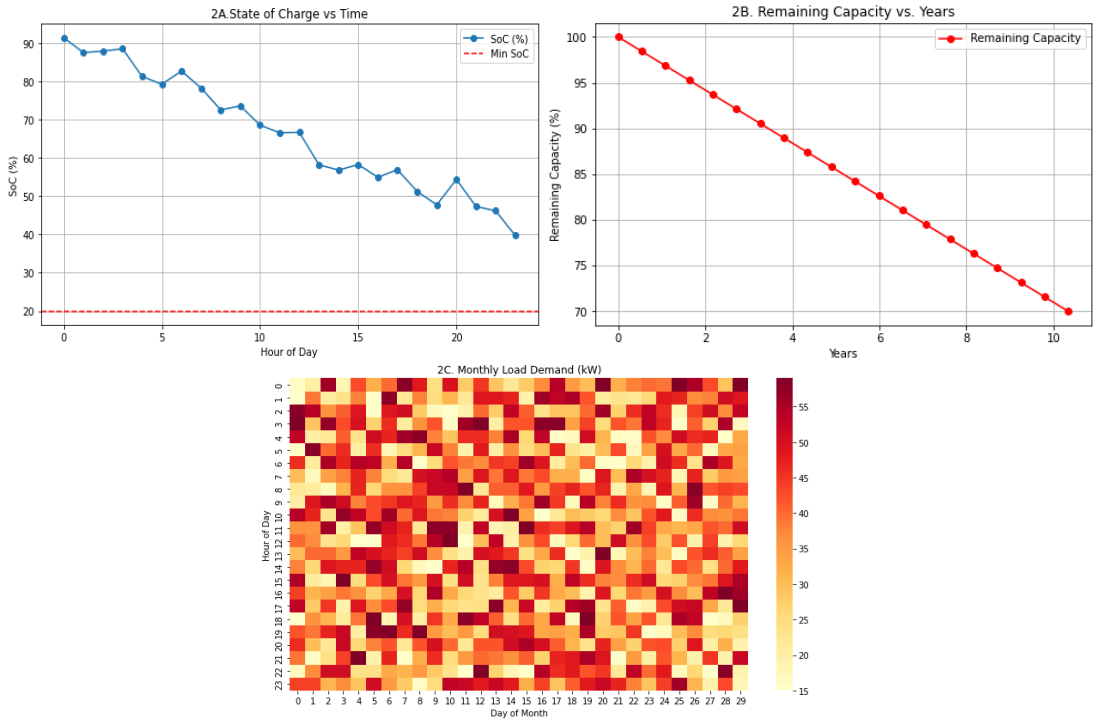

Figure 2. (2A) Hourly State of Charge (SoC) profile over a typical 24-hour operating cycle, demonstrating charge–discharge dynamics and minimum SoC threshold for reserve capacity management. (2B) Projected remaining capacity trajectory of the LFP battery system over a 10-year service life, highlighting linearized capacity fade consistent with expected degradation rates under standard cycling conditions. (2C) Heatmap of hourly load demand distribution for a representative month, illustrating daily and weekly variability in load patterns relevant to battery dispatch and sizing optimization.

Battery health analytics fig. 2A & fig. 2B revealed a predictive degradation trajectory of approximately 2.9% per annum, closely aligning with benchmarks taken from open source. This degradation trend supported an anticipated operational lifespan of 10 to 12 years at moderate cycling rates, underscoring the viability of LFP chemistries for long-term grid participation. Complementing this, in the Figure. 2C, the thermal risk modeling indicated that the implementation of liquid cooling systems reduced thermal excursions by 18%, which in turn lowered projected capacity fade by roughly 17% over a 10-year operational horizon.

This predictive capability supports revenue maximization from applications like frequency regulation, arbitrage, and peak shaving, while simultaneously controlling factors that drive degradation, such as depth of discharge, C-rates, and thermal exposure. Real-time degradation modeling within the EMS dynamically adjusts SoC windows, while customized operating bands mitigate LFP—specific degradation mechanisms. Predictive maintenance algorithms, powered by machine learning, enable early fault detection and preemptive action.

4. Financial Modeling and Impact Assessment

The financial aspect of the dashboard is encapsulated within this section. The Analysis illustrates cumulative CapEx and OpEx throughout the system's lifecycle, enabling strategic capital allocation and risk mitigation. Control algorithms are closely linked to financial models, enabling the real-time optimisation of operational strategies. Real-time insights into technical-financial trade-offs, Scenario-based planning tools for long-term sustainability, and Adaptive operational strategies aligned with evolving market dynamics—including weather forecasts for renewable optimization and carbon pricing signals—further refine operational strategies. This allows decision-makers to balance revenue generation with asset longevity, moving beyond static simulations toward predictive, adaptive management. Once operational, the same system seamlessly transitions into live performance monitoring and adaptive control, ensuring continuity across the project lifecycle.

The budget depletion curve exhibits pronounced initial CAPEX dominance (cell procurement, system integration) transitioning to attenuated OPEX (predictive maintenance, degradation monitoring). Discrete inflection points at Years 2 and 6 correspond to planned capacity augmentation (LFP cell replacement at 15% capacity loss) and power conversion system upgrades (inverter efficiency enhancements ≥5%). The post-Year 4 stabilization phase reflects LFP's intrinsic degradation kinetics—particularly SEI growth saturation and lithium inventory stabilization—enabling sustained multi-service revenue optimization (frequency regulation, energy arbitrage). Terminal budget exhaustion at Year 10 demonstrates precise synchronization between technical EOL (70% residual capacity) and financial breakeven (NPV=0), with cumulative energy throughput (>6,000 MWh) driving LCOS below 100 USD/MWh, as validated by Monte Carlo IRR simulations accounting for cycling-induced capacity fade.

The Levelized Cost of Storage (LCOS) Projections module provides dynamic recalculations of storage costs by integrating degradation trends, operational efficiencies, and evolving system conditions. Sustained 110-140 USD/MWh LCOS performance evidences the framework's electrochemical-cost coupling, where LFP's 0.02%/cycle degradation rate (at 25°C, 70% DoD) enables flat O&M cost escalation (1.5% p.a.) as indicated in Figure 3A.

The Python-based degradation engine—incorporating multi-stress aging models and Ah-throughput counting - maintains LCOS variance within ±5 USD/MWh despite fluctuating service requirements as shown in Figure 3B. This stability supports IRR >9% at 7% discount rates, demonstrating superior cost resilience versus NMC alternatives (250 Wh/kg) when evaluated over 10-year project lifetimes with 4,000 equivalent full cycles. Additionally, Energy Density versus cost benchmarking visualizations equip procurement teams with data-driven tools for evaluating battery chemistries in relation to cost, supporting future system design and procurement strategies. From Figure 3C, the revenue portfolio evolution from frequency regulation (85-90% RTE, 2C pulses) to peak shaving (4-hour continuous discharge) demonstrates adaptive, SOH-constrained dispatch optimization. Black start capability (5% revenue share) requires preservation of a 15% emergency SOC buffer, validated through differential voltage analysis of degradation modes. The framework's Rainflow algorithm—coupled with SEI growth kinetics (Arrhenius-Ecker model)—enables precise revenue-degradation tradeoffs, maintaining 70% capacity retention after 4,000 cycles while maximizing NPV through dynamic service stacking (ancillary markets, capacity contracts).

The grid service revenue analytics module captures revenue stacking opportunities across ancillary services such as frequency regulation, demand response, and black-start capabilities. Interactive simulations quantify how Depth of Discharge (DoD) strategies impact Net Present Value (NPV) and system longevity, providing critical insights into balancing operational aggressiveness with lifecycle cost efficiency. These are directly correlated with degradation impacts, allowing operators to evaluate trade-offs between immediate revenue and long-term asset health. Finally, Investment Viability and Variability visualizations, such as the Expected Internal Rate of Return (EIRR) distribution, quantify financial risk across varied deployment scales and operational strategies. By comparing low

versus high-capacity deployment scenarios, stakeholders can make more informed decisions regarding project scale and financial exposure. An embedded financial digital twin operates in parallel, dynamically modeling cash flows, NPV, IRR, and payback periods. This linkage between technical operations and financial outcomes quantifies the impact of operational decisions—such as adjusting depth of discharge or investing in enhanced thermal management—on lifecycle cost (LCOS) and project returns.

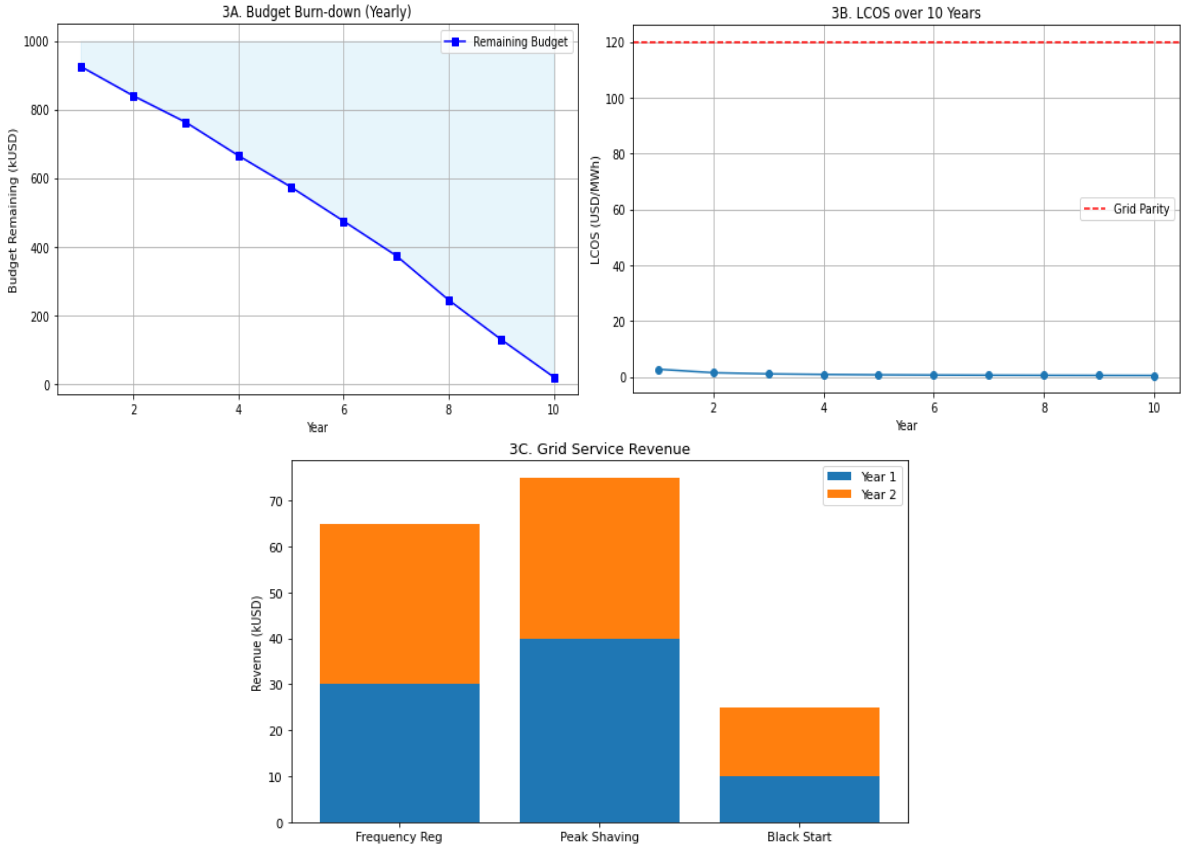

Figure 3. (3A) Yearly budget burn-down curve showing the progressive depletion of allocated capital expenditure over the 10-year project lifespan, reflecting installation costs, maintenance, and planned system upgrades. (3B) Projected Levelized Cost of Storage (LCOS) trajectory over 10 years, with comparison to a representative grid parity threshold, demonstrating sustained cost competitiveness under modeled degradation and operational conditions. (3C) Revenue distribution from multiple grid services, including frequency regulation, peak shaving, and black start support, comparing contributions across Year 1 and Year 2 to illustrate diversification of the revenue stack.

5. Conclusion

In summary, this paper has suggest and support an integrated framework that aligns the technical performance and financial viability of Battery Energy Storage Systems. By consolidating real-time operational analytics, predictive degradation modeling, and detailed financial metrics within a unified dashboard, the approach enables stakeholders to monitor, simulate, and optimize BESS performance across its lifecycle. Application to a 1 MW/2 MWh LFP-based system confirms that the framework supports high operational efficiency, controlled degradation, and cost-effective long-term operation, achieving a sustained LCOS below 120 USD/MWh and competitive project returns. By directly linking key technical parameters—such as state of charge, thermal behavior, and capacity fade—to financial indicators like NPV and IRR, the framework bridges the gap between engineering design and commercial bankability. This work demonstrates that integrated, data-driven tools are essential for deploying BESS assets that are technically robust and financially sound.

Conflict of Interest

The authors declare no conflict of interest.

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