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RESEARCH ARTICLE

Utility-Scale Battery Energy Storage Systems–Field Pilot Unit Experience, Analysis, and Review of Technological Advancements

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ABSTRACT Utility-scale Battery Energy Storage Systems (BESS) are becoming increasingly important in modern power systems, providing services ranging from backup support to load balancing and peak shaving. The long-term operational performance and reliability of these systems with expanding deployment remain insufficiently documented. This paper provides an operational assessment of a 1MW/2MWh utility-scale BESS alongside a systematic review of technology developments across major subsystems. Operational metrics including round-trip efficiency (RTE), outage characteristics, and degradation patterns are examined to identify performance trends and the underlying causes of outages. In addition, testing and operational principles aligned with utility practice and standards are presented to ensure the safety and reliability of batteries. These field experiences are compared with technological advancements in BESS subsystems like thermal management systems, power conversion systems (PCS), and battery management systems (BMS). The analysis shows that early challenges such as cooling inefficiencies, limitations in power electronics, and frequent unplanned outages correspond with subsequent improvements in thermal performance, diagnostics, modularity, and control strategies. By comparing operational performance with technological enhancements, this study demonstrates how field experiences have influenced research directions and design improvements. The results provide important insights to utilities, researchers, and policy makers seeking to enhance the reliability and life-cycle performance of next-generation grid-scale BESS deployments.

INDEX TERMS Battery energy storage system (BESS), battery management system, degradation, operational analysis, pilot unit, power conversion system, reliability, round-trip efficiency, safety, utility-scale, technological evolution.

I. INTRODUCTION

Growing computational demands from artificial intelligence, cloud services, and data processing have accelerated data center deployment, leading to rising electric power demand and their characteristic load profiles, combined with the proliferation of intermittent renewable energy can stress electricity infrastructure [1]. Meeting these operational requirements necessitates solutions that deliver stable and reliable power while maintaining flexibility during peak periods and grid disruptions. Battery Energy Storage Systems (BESS) are one of the effective technologies available for peak shaving, load management, and resilience enhancement, when deployed and operated with an emphasis on long-term reliability and safety [2], [3].

As utility-scale BESS deployments continue to increase, long-term, high-resolution operational field data may be essential in developing critical operational strategies that ensure safety, reliability, and reduced degradation rates. In this context, insights from the Electric Power Research

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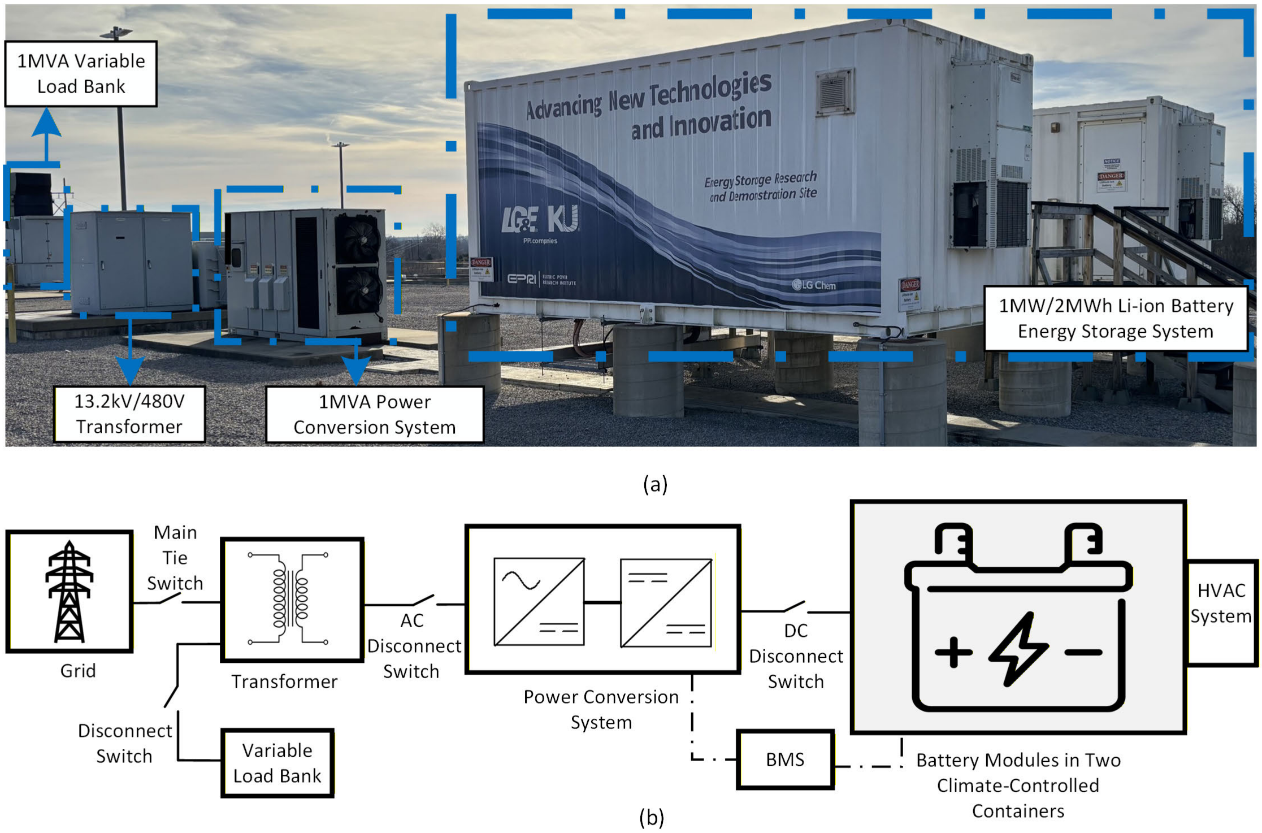


FIGURE 1. The BESS deployed at the PPL Renewable Integration Research Facility, shown in (a), comprises a 1-MW/2-MWh battery array housed in two containers, a 1-MVA bidirectional inverter, a 1-MVA variable load bank, and a 13.2-kV/480-V transformer. The battery configuration consists of 20 racks, each containing 17 modules of 14 Li-ion cells, evenly distributed across the two containers. A block diagram of the grid-connected field pilot system is presented in (b), illustrating the interconnection between major subsystems.

Institute's analyses derived from its BESS Failure Incident Database, underscore the importance of systematically understanding failure modes and root causes to guide effective operational and safety practices [4].

Data-driven degradation models depend on long-term operational datasets to quantify indicators such as internal resistance growth and remaining useful life, as demonstrated by studies linking temperature and depth-of-discharge [5]. Recent studies demonstrate that degradation metrics extracted from long-term operational datasets can be integrated directly into optimal dispatch frameworks, highlighting the importance of high-resolution field data for both degradation analysis and operational decision-making [6].

Most existing BESS studies rely on model-based approaches with simplifying assumptions that may not accurately capture field operational behavior. Authors in [7] and [8] employed a simplified expression for BESS power flow in analyzing multi-MW grid connected solar PV farm configurations with integrated battery systems. These simplified models neglected the effects of battery system efficiency losses and capacity degradation due to aging, which may introduce non-negligible error in the projected system performance. The long-term field operational data and analysis from the grid-connected BESS operated under real-world dispatch scenarios offers direct insight into practical system performance, including round-trip efficiency and degradation patterns.

This paper presents an analysis of multi-year, high-resolution operational data from the 1MW / 2MWh lithium-ion BESS field pilot unit at the PPL Renewable Integration Research Facility. The study synthesizes operational experience and insights derived from system operation and collaborative research activities conducted on the battery, with particular emphasis on safety, reliability, degradation, and performance under real-world conditions. Nine years of cell-level, sub-second, and publicly accessible data have been collected and shared to advance future BESS.

In addition, the paper reviews technological advancements in modern BESS architectures that address limitations observed in early-generation systems. This contextualizes how field-derived insights have informed the evolution of utility-scale energy storage design and operation. The experiences derived from the long term operation has also influenced the design of the 125MW / 500 MWh system being built at the same facility.

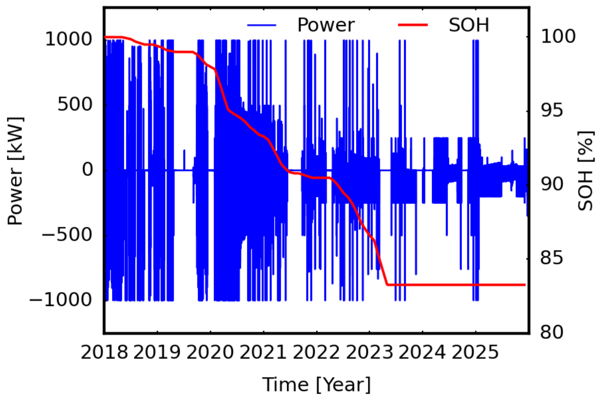


FIGURE 2. Temporal variation of system power and BMS reported SOH from 2018 to 2025, showing periods of intensive cycling in early years and reduced operation with SOH stabilization after 2023.

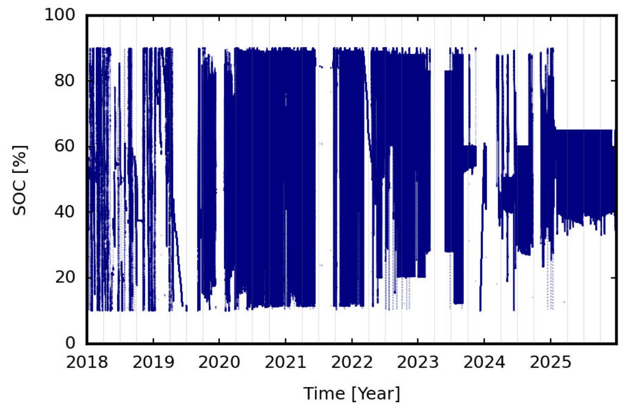


FIGURE 3. BMS-reported state-of-charge from 2018–2025 illustrating wide fluctuations during high-utilization years and a noticeably reduced SOC window in 2024 reflecting limited operational range.

TABLE 1. Annual Equivalent Cycling Frequency (EFC) based on total energy throughput.

Year	Charged Energy [kWh]	Discharged Energy [kWh]	Total Energy Throughput [kWh]	Equivalent Full Cycle
2018	222,208	187,749	409,957	102.49
2019	170,603	140,887	311,489	77.87
2020	504,874	437,572	942,444	235.61
2021	387,471	339,522	726,991	181.75
2022	329,181	275,468	604,649	151.16
2023	217,015	177,371	394,386	98.60
2024	115,550	79,429	194,978	48.74
2025	245,720	192,862	438,580	109.65

The remainder of this paper is organized as follows. Section II describes the BESS configuration and summarizes research activities conducted on the system. Section III presents the long-term operational dataset and data acquisition framework of the field pilot unit. The battery's outage characteristics and operating conditions are examined in Section IV, followed by an analysis of round-trip efficiency and degradation behavior in Sections V and VI, respectively. Section VII reports results from standardized field tests and discusses operational practices emphasizing safety. A review of technological advancements in BESS and their relevance to addressing early-generation limitations is provided in Section VIII. Section IX discusses the results and derived insights that support safe and reliable BESS operation, and Section X concludes the paper by summarizing the key findings.

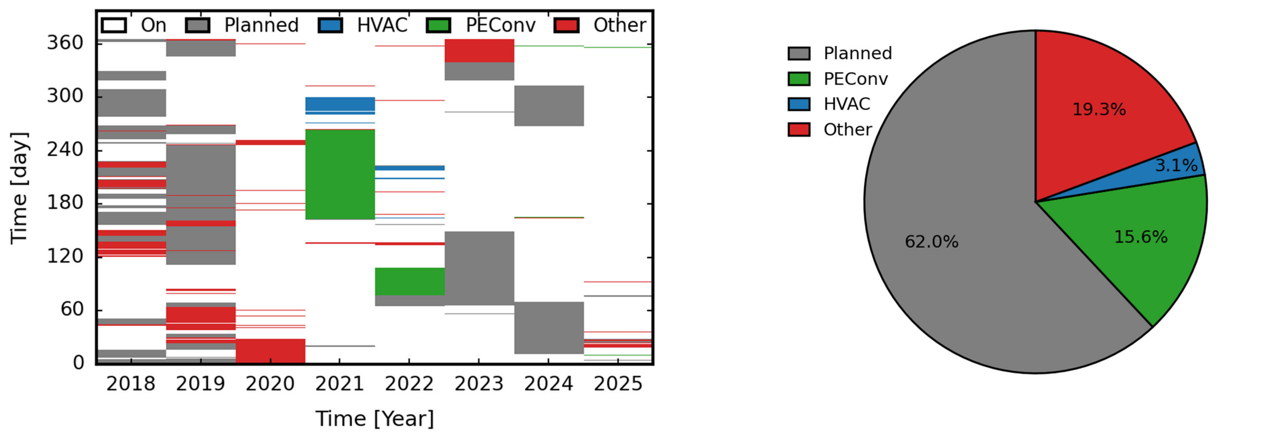
II. BESS FIELD PILOT PROJECT AT THE E.W. BROWN RESEARCH SITE

The utility-scale Li-ion battery energy storage system at the PPL Renewable Integration Research Facility became operational in 2017. At the time, the pilot unit represented a significantly sized utility-scale BESS for research and testing, the first in the commonwealth of Kentucky. The installation includes a 1MW/2MWh battery system, a 1MVA bi-directional power conversion system (PCS), a 13.2kV/480V step-up transformer, and a 1MVA programmable load bank, as shown in Fig. 1(a). The block diagram of the setup is illustrated in Fig. 1(b), which demonstrates the integration between subsystems.

The battery system has 20 racks distributed evenly between two climate-controlled containers, with 17 modules of 14 Li-ion cells with nominal voltage of 51.8V and 126Ah rating per module in each rack, totaling 4,760 cells configured in series-parallel arrangement.

An integrated battery management system (BMS) allows individual cell monitoring, state-of-charge balancing, state-of-health estimation, and data logging. The PCS has a bi-directional two-level converter with rated operation in a DC-link voltage range of 740V to 1150V with a fixed 480V AC output voltage. For islanded and microgrid operation and to minimize grid disturbance during testing, the battery system is integrated with a 1MVA programmable load bank with capability to absorb 1MW resistive power and supply or absorb 600kVAr reactive power in 5kVA intervals.

The 1MW/2MWh BESS has served as an experimental platform for a coordinated series of research on the integration of utility-scale energy storage with photovoltaic (PV) generation. Rallabandi et al. first analyzed the combined PV-BESS operation using a modified IEEE 14-bus system, demonstrating the BESS's effectiveness in frequency regulation and PV power smoothing [8]. This work was further advanced by Akeyo et al. with a proposed architecture in which the battery and PV array share a single bidirectional DC-DC converter, enabling simultaneous MPPT and charge management. This topology demonstrated enhanced MPPT stability and yielded capacity factor improvement up to 20% [9]. A systematic sizing methodology for DC-connected BESS was developed, using empirical irradiance and temperature data from the E.W. Brown site, demonstrating that



(a) (b)

FIGURE 4. Categorized outage timeline for the BESS from 2018 to 2025 is illustrated in (a), showing planned downtime and unplanned outages associated with power electronics conversion system (PEConv), HVAC, and other causes, with uptime periods indicated in white. The pie chart, shown in (b), summarizes the proportional contribution of each outage category to total downtime over the study period.

TABLE 2. Breakdown of annual BESS operational availability, with downtime categorized into planned and unplanned outages.

Metric [%]	2018	2019	2020	2021	2022	2023	2024	2025
Uptime	54.4	38.5	89.3	65.4	83.4	64.0	70.5	96.4
Planned Outage	34.5	49.3	0.3	0.8	3.8	28.8	28.5	1.4
Unplanned Outage	11.1	12.1	10.3	33.8	12.8	7.2	1.0	2.1
HVAC	*0.0*	*0.0*	*0.0*	*5.2*	*2.2*	*0.0*	*0.0*	*0.0*
PEConv	*0.0*	*0.0*	*0.0*	*27.8*	*8.7*	*0.0*	*0.3*	*0.3*
Other	*11.1*	*12.1*	*10.3*	*0.8*	*1.9*	*7.2*	*0.7*	*1.8*

a 2MWh battery could recover up to 360MWh of curtailed energy annually [7].

Following initial PV–BESS integration studies, subsequent research focused on detailed characterization and modeling of the experimental BESS at the PPL research facility. A runtime equivalent circuit model of the utility-scale Li-ion BESS was developed based on pulse-discharge measurements, achieving 99% voltage accuracy in PSCAD/EMTDC simulations and demonstrating autonomous frequency regulation capability for grid-support applications [10]. This was complemented by a field-validated parameter estimation procedure. The study proposed a standardized charge/discharge test to derive equivalent circuit parameters directly from site measurements, achieving less than 0.8% voltage error while accurately capturing SOC-dependent dynamic behavior [11].

Extending this framework, a multi-scale modeling hierarchy spanning cell, module, rack, and system levels was developed, confirming that a single sub-component model could be scaled to represent the entire system within 1% average voltage deviation under active BMS supervision [12]. The validated equivalent circuit model was employed to develop an optimization algorithm for multi-unit BESS operation aimed at minimizing degradation [6].

Standardized testing procedures developed by the Electric Power Research Institute (EPRI) were implemented on the experimental BESS setup to evaluate operational performance under utility conditions. Tests included available energy, charge/discharge duration, round-trip efficiency, and self-discharge rate, with results supporting the development of an equivalent battery model that achieved up to 99.9% accuracy in voltage prediction using an improved cell parameter estimation method [13].

Research utilizing the utility-scale BESS cells led to the development of two patented methods for recycling and material recovery from end-of-life lithium-ion batteries. The first patent outlines an integrated process involving roasting of black mass, aqueous leaching with wet magnetic separation, and electrochemical purification to extract high-purity lithium and enrich Ni–Co metals [14]. The second patent details the recovery of valuable metals and graphite through thermal decomposition, lithium extraction, and staged magnetic separation [15]. Together, these innovations demonstrate how experimental work on the BESS platform directly informed sustainable recycling technologies that advance circular economy practices in large-scale energy storage.

EPRI investigations using the 1MW/2MWh E.W. Brown BESS demonstrated the importance of detailed operational data for evaluating utility-scale storage systems. Analysis of sparse and robust datasets showed that while limited data reveal overall reliability trends, high-resolution Brown BESS data enabled identification of component faults and degradation mechanisms [16]. The complementary degradation analysis used standardized reference performance tests and long-term field data to estimate capacity fade and state-of-health decline. This highlights the relationship between cell balancing activity, standby losses, and reduced efficiency across operating years [17].

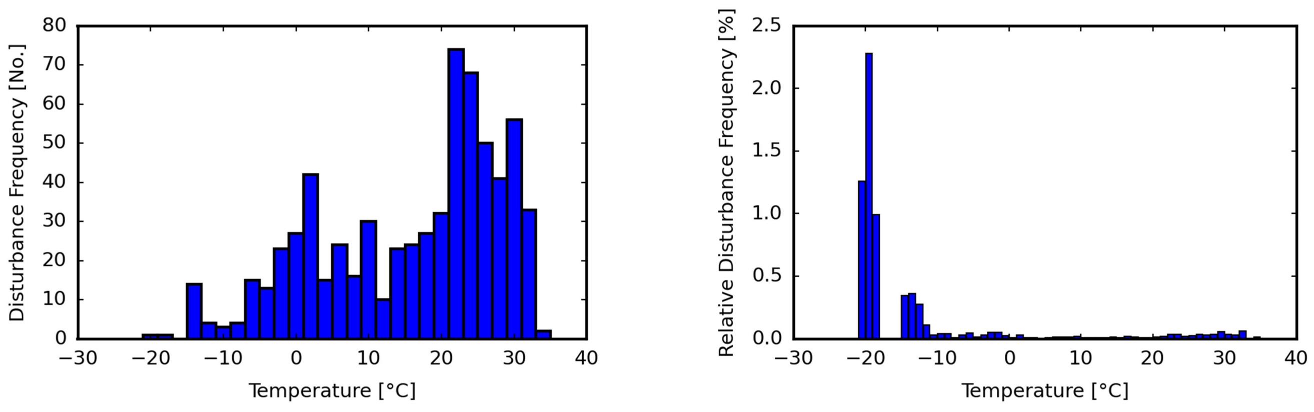


FIGURE 5. Histograms of unplanned battery disturbance events as a function of ambient temperature: (a) absolute disturbance count and (b) relative disturbance frequency normalized by time spent in the temperature range. While moderate to high temperatures exhibit higher absolute disturbance occurrences, cold weather conditions, particularly below 0°C, demonstrate significantly elevated disturbance rates.

Thermal runaway in lithium-ion BESS is predominantly driven by thermal, mechanical, and operational abuse. Field operation of the pilot system prioritized safety and informed utility-scale practices, including conservative state-of-charge limits, redundant HVAC, and continuous cell-level monitoring. The installation also marked the world's first commercial utility deployment of the Li-ion Tamer off-gas detection system, enabling early detection of chemical precursors to thermal runaway ahead of temperature or smoke-based sensing, thereby strengthening proactive risk mitigation in grid-scale BESS operation [18].

Beyond the published literature and academic research conducted on the pilot system, the facility has served as an educational resource for energy storage professionals and researchers evaluating utility-scale safety measures. In 2019, a delegation of energy storage leaders from the South Korean government conducted a technical assessment of the system architecture and safety protocols.

Subsequently, in 2022, over 100 utility representatives from international organizations participated in facility tours through the Electric Power Research Institute (EPRI) Energy Storage and Distributed Generation Program (P94). Regular site visits by University of Kentucky College of Engineering students provide educational opportunities for engineering workforce development in energy storage technologies. Additionally, facility operators conduct annual battery safety trainings for regional fire departments, contributing to emergency response preparedness for grid-scale BESS installations.

Collectively, the studies conducted based on the pilot unit have built an experimental foundation for utility-scale energy storage systems, advancing battery modeling, control strategies, degradation assessment, and recycling innovations. The installation's role as an international reference site and educational platform has facilitated knowledge transfer to utility operators, government agencies, emergency responders, and engineering students. These combined contributions demonstrate the critical role of field-validated data, operational safety practices, and collaborative knowledge-sharing in guiding the development and safe deployment of future grid-integrated storage technologies.

III. LONG-TERM OPERATION AND DATA COLLECTION OF THE FIELD PILOT UNIT

Under field operating conditions, the utility-scale lithium-ion BESS is continuously monitored. A time-stamped record of electrical, thermal, and operational behavior was obtained by collecting high resolution multi-year datasets from the BMS. Systematic data collection for the BESS started in 2018, after commissioning and acceptance testing were concluded in 2017. Real-time battery data, ambient conditions, along with wind and solar generation are made publicly available, with sub-second cell level data shared with researchers, national laboratories, and EPRI [19], [20], [21].

State-of-charge (SOC), estimated state-of-health (SOH), DC voltage and current, average and extreme cell voltages, and AC real and reactive power are among the key variables that are logged. Additionally recorded were operational parameters like power factor, available power, control setpoints, unit status (active and running), and mode of operation. Estimating round-trip efficiency and evaluating cycle-related degradation are made possible by energy throughput data, which includes charge and discharge energy.

Module-level maximum and minimum temperatures, container temperatures, and HVAC operations are examples of thermal variables that are recorded to support the assessment of auxiliary consumption and thermal management techniques. The BMS fault logs capture events associated with the battery, the climate-controlled containers, and power conversion system. Complementary outage and downtime data recorded by system operators provide essential data for assessing system availability and reliability.

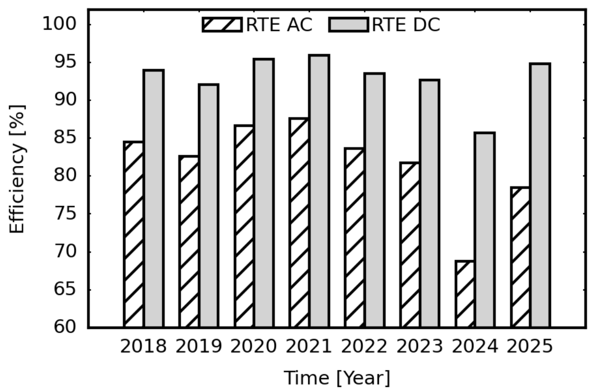


FIGURE 6. Annual AC and DC round-trip efficiency calculated from total charged and discharged energy between 2018 and 2025.

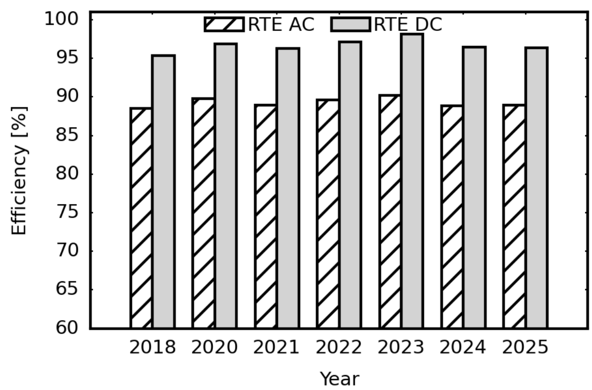


FIGURE 7. AC and DC round-trip efficiency obtained from annual reference performance tests (RPTs) conducted between 2018 and 2025.

These measurements and logs collectively provide a high-resolution dataset that facilitates a comprehensive assessment of the functionality, degradation, and resilience of utility-scale BESS in prolonged field operation.

The charge-discharge power and state-of-health, shown in Fig. 2, demonstrate temporal variation from 2018 to 2025, illustrating changes in operational intensity over the deployment period. Frequent cycling and high depth-of-discharge patterns predominate during the initial operation phase, and notable power amplitude variations indicate intensive capacity utilization. A progressive SOH decline is observed from roughly 100% to 84% by 2023.

To characterize the cycling behavior under partial cycling conditions, an Equivalent Full Cycle (EFC) analysis was performed. This approach provides a standardized measure of total charge and discharge throughput normalized to the rated capacity, making it particularly valuable in real-world applications where batteries rarely undergo complete charge-discharge cycles and conventional cycle counting may be an inadequate measure of true cumulative cycling. The EFC can be expressed as [22]:

$$\mathrm{EFC} = \frac{A_h^c + A_h^d}{2 \cdot C}, \tag{1}$$

where A_h^c and A_h^d are the total charged and discharged energy throughput respectively, and C is the rated battery capacity.

As presented in Table 1, the results reveal a reduction in cycling frequency during the later operational periods, consistent with a transition toward more conservative operational strategies. Particularly, a reduction in EFC of approximately 60% is observed from 2020 to 2023. This reduction in cumulative cycling stress may be a contributing factor to the observed stabilization of the SOH degradation rate in subsequent years.

These findings are corroborated by the state of charge profile in Fig. 3, which displays dynamic and wide-ranging fluctuations during the early operation years, characterized by intense cycling. The deeper discharge depths and increased throughput noted during this phase are consistent with these fluctuations. From 2024 onward, both SOC variability and power activity decrease noticeably, with the operational power and SOC window narrowing considerably.

TABLE 3. Annual BESS charging, discharging, and round-trip efficiency metrics.

Year	Charged AC Energy [kWh]	Discharged AC Energy [kWh]	RTE AC [%]	Charged DC Energy [kWh]	Discharged DC Energy [kWh]	RTE DC [%]
2018	222,208	187,749	84.49	209,589	196,987	93.99
2019	170,603	140,887	82.58	161,299	148,537	92.09
2020	504,874	437,572	86.67	481,177	459,233	95.44
2021	387,471	339,522	87.63	370,633	355,665	95.96
2022	329,181	275,468	83.68	311,357	291,181	93.52
2023	217,015	177,371	81.73	202,912	188,117	92.71
2024	115,550	79,429	68.74	105,545	90,445.9	85.69
2025	245,720	192,862	78.49	225,654	214,051	94.86

This highlights an inverse relationship between battery usage and longevity, as measured by state-of-health and cycling characteristics, showing that degradation increased with use but was meaningfully reduced under less aggressive charge and discharge conditions. The narrower charge-discharge range is a strategic operational adjustment aimed at reducing electrochemical stress on the cell, ensuring safety, and maintaining system performance as the battery ages. Batteries that are operated aggressively will have a significantly reduced lifespan, while controlled duty cycle operation may extend operational lifespan.

IV. BESS OUTAGE CHARACTERISTICS AND OPERATING CONDITIONS

Scheduled and unforeseen operational events may impact the performance and availability of battery energy storage systems. Planned downtime includes periods associated with

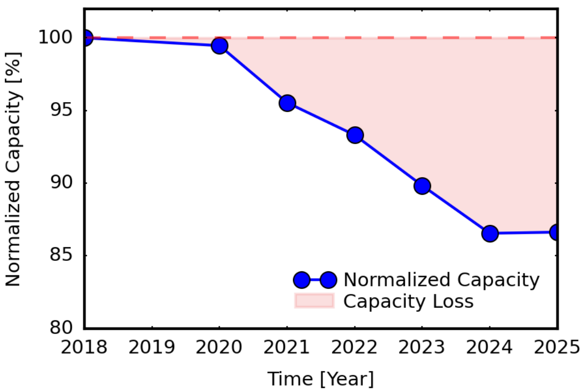


FIGURE 8. Normalized capacity of the utility-scale BESS from 2018 to 2025, showing cumulative degradation relative to first-year RPT baseline.

TABLE 4. Summary of performance metrics based on reference performance tests.

Year	RTE (AC) [%]	RTE (DC) [%]	Normalized Capacity [%]	Degradation Rate [%/year]
2018	88.5	95.4	100.0	0.0
2020	89.7	96.9	99.5	0.3
2021	88.9	96.3	95.5	4.0
2022	89.6	97.1	93.3	2.2
2023	90.2	98.1	89.8	3.5
2024	88.8	96.5	86.6	3.3
2025	88.9	96.4	86.6	0.0

preventive maintenance, infrastructure upgrades, generation interconnection activities, firmware updates, or grid-interfacing specifications. On the other hand, forced outages could be caused by control system disruptions, hardware malfunctions, or communication failures. Given its operation as a pilot installation, the system utilized operator-initiated restoration procedures following disturbances, since every event required detailed investigation and evaluation. Depending on their occurrence and duration, these events may contribute to drops in round-trip efficiency and introduce fluctuations in energy throughput. The BESS's reported outage types, durations, and frequency are categorized and analyzed in this section.

As shown in Fig. 4 (a), the operational status of the system is categorized into five distinct classifications: normal operation denoted as "ON" (white), planned downtime (gray), and three categories of unplanned outages including power electronics converter failures (green), HVAC-related disturbances (blue), and outages designated as "other" (red). The "other" category encompasses issues not directly attributable to PCS or HVAC subsystems, such as communication failures, protective relay trips, or analogous system-level failures. These outages are broadly categorized as unplanned, arising from the failure of system components within the pilot unit as presented in Table 2. Illustrated in Fig. 4(b) is a summary of the proportional contribution of each outage category to the total downtime over the study period.

In 2019, the battery operators initiated an extended safety-related outage following the April battery energy storage system incident that hospitalized four firefighters in Surprise, Arizona, which involved a sister system of identical capacity and the same LG Chem lithium-ion technology [23]. The battery operators de-energized the pilot system as a precautionary measure pending completion of a comprehensive investigation and safety audit and maintained the system offline until all safety verification and emergency preparedness requirements were satisfied.

Prior to re-energizing the system, the battery operators conducted training for local fire departments and utility personnel, installed hazard signage, established remotely accessible emergency stop controls at a safe distance from the battery enclosure, and implemented a formal emergency response plan. During this outage period, operators performed limited maintenance charging cycles to prevent excessive state-of-charge depletion while maintaining non-operational system status. As a result of the Surprise Arizona battery fire, operations on the pilot system were changed to limit the maximum state-of-charge. In December, there was a planned firmware upgrade lasting about 29 days.

The first few months of 2020 recorded many short, unplanned events that were classified as "other". The system had its longest unplanned outage in 2021, which lasted 100 days and was caused by a power conversion system failure. Additionally, approximately 19 days of HVAC downtime resulted from a fan motor failure, a control board defect in container 2, and routine scheduled maintenance.

In 2022, the LEMB and LEMC driver boards caused a 30-day PEConv outage and about a week of intermittent HVAC disruptions. Starting in 2023, the operational profile changed mostly to planned maintenance tasks. The planned outages in early and late 2023 were conducted to facilitate the installation of dual-axis solar trackers and a wind turbine, respectively. In 2024, two major planned outages were recorded: a 60-day shutdown in January initiated as a safety precaution after a fire at another facility coupled with an EPRI safety advisory on cell balancing verification and a 45-day period in August for installation of single-axis solar trackers.

A critical insight is observed when examining the relationship between ambient temperature and unplanned outages in the pilot system. The total disturbance count and relative frequency of disturbances per minute within discrete temperature bins is presented in Fig. 5. The temperature fault analysis reports a correlation between unplanned disturbance normalized by time spent at each ambient temperature, which is intended to isolate failure rather than total downtime as illustrated in Fig. 5(b). The analysis reveals that system experiences higher incidence of unplanned fault events when temperatures drop below 0°C compared to the 0-40°C range.

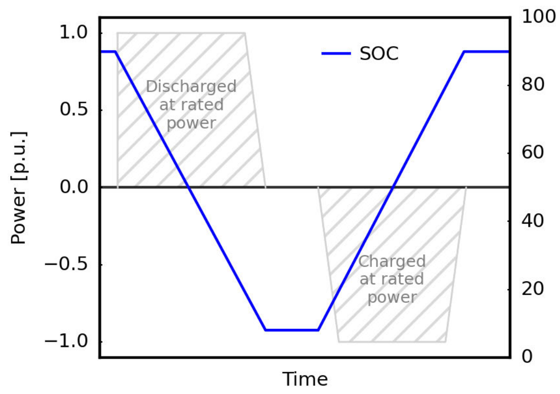


FIGURE 9. EPRI Reference Performance Test (RPT) protocol illustrating full-power discharge, rest period, and full-power charge phases, with the state-of-charge (SOC) trajectory limited between defined upper and lower bounds.

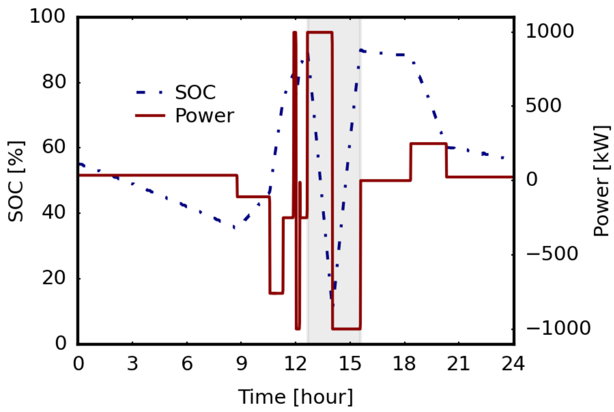


FIGURE 10. Example implementation of EPRI's reference performance test showing a full charge–discharge cycle used to evaluate system capacity, round-trip efficiency, and estimate degradation.

This temperature-dependent pattern presents an operational challenge, as the battery is most prone to disturbances during extreme cold weather events, when grid support is most needed to meet peak demands. Beyond reliability concerns, disturbances occurring below freezing temperatures may pose safety risks by triggering cascading failures where other components shut down or freeze, potentially leading to thermal abuse conditions that can escalate to thermal runaway of the BESS [18].

As summarized in Table 2, the sustained multi-year data collection and systematic event categorization show a shift from reactive failure response to proactive, reliability-focused, and safety-oriented operational practices. This increased the system up-time to approximately 96% at the end of 2025. The majority of planned outages in the earlier operational years were implemented at management's directive as precautionary safety measures following prior incidents or to ensure personnel safety during on-site construction activities.

V. ANALYSIS OF ROUND-TRIP EFFICIENCY

The ratio of energy discharged to energy charged over the duration of a full operating cycle is known as round-trip efficiency (RTE), and it is a performance indicator for BESS [24]. This parameter captures the combined impact of electrochemical, power conversion, and auxiliary subsystem losses and indicates the percentage of stored energy recoverable for grid injection. Both the alternating current (AC) and direct current (DC) measurement points can be used to evaluate RTE. Direct current RTE, which is measured at the battery terminals, primarily represents ohmic and electrochemical losses that are present in the cell and module assemblies.

On the other hand, additional losses attributable to the PCS and auxiliary equipment like thermal management systems are included in AC RTE, which is measured at the grid interconnection point. The AC RTE provides a system-level evaluation that is more representative of operational efficiency and grid-scale application performance, whereas DC RTE is suitable for describing intrinsic battery performance. The round-trip efficiency can be expressed as:

$$\eta_{\text{RTE}} = \frac{E_{\text{discharge}}}{E_{\text{charge}}} \times 100\%, \qquad (2)$$

where $E_{\text{discharge}}$ is the total discharged energy and E_{charge} is the total charged energy over a defined period.

Two complementary approaches are employed to evaluate the round-trip efficiency of the battery. To create consistent efficiency baselines, the first method uses reference performance tests (RPTs), in which standardized charge-discharge cycles are conducted on a regular basis. These measurements offer consistent benchmarks across the operational lifespan that facilitate performance tracking over time.

The second approach aggregates the total charge and discharge energy from continual field operation using cumulative annual energy throughput. When RPT data is scarce or unavailable, this method is especially helpful in characterizing efficiency under real-world operating conditions. A combination of these two techniques enable an assessment of the evolution of long-term efficiency as well as measurement of power conversion and auxiliary subsystem losses in practical deployment scenarios.

Based on the annual cumulative charged and discharged energy, Fig. 6 shows the temporal evolution of AC and DC round-trip efficiency from 2018 to 2025. These field-derived metrics show the combined impact of power electronics performance, control settings, and dispatch strategies in addition to the inherent system efficiency. The power conversion system and auxiliary losses may account for the relatively lower AC-RTE (82–87%) during the observation period, whereas DC-RTE stays consistently high (92–96%).

In 2024, there is a noticeable reduction in both DC and AC RTE, with efficiency dropping below 90% and 70% respectively, as presented in Table 3 and a reduced cycling rate (see Table 1). This is as a result of the purposeful operational change made by the operator to improve safety margins and system reliability. The usable state-of-charge window was reduced from 10–90% to 35–65%, and the maximum dispatch power output was decreased to 200 kW.

The findings presented in [25] and EPRI's analysis of battery energy storage system failure mechanisms [4], which both show a relationship between SOC operating limits and battery safety, served as the basis for this decision. Due to reduced inverter efficiency under partial loading conditions, lower dispatch power may lead to increased AC-side conversion losses, thereby reducing effective energy throughput and resulting in a noticeable deviation from the consistent approximately 10% difference between AC and DC RTE [26].

To support these operational findings, RTE values from reference performance tests carried out during the same time period are shown in Fig. 7. Charge/discharge rates, SOC limits, and rest periods are all set under this standardized protocol, allowing for reliable annual benchmarking [24]. The DC-RTE values from the RPT stay high (95–97%) across the years, which may mean stable battery performance. Comparatively, the AC-RTE is lower, ranging from 87–90%, which may reflect the conversion and auxiliary losses previously discussed. The relatively small difference between AC-RTE and DC-RTE, which stayed between 5% and 8% each year, may suggest that these losses were mostly the same during the study period.

VI. DEGRADATION ANALYSIS

Battery degradation is characterized by the progressive decline in capacity, power delivery capability, and efficiency resulting from chemical, physical, and mechanical processes. Degradation mechanisms may include solid-electrolyte interphase (SEI) formation, electrolyte decomposition, structural changes in electrode materials, cycling-induced stress, and temperature-related effects [27], [28].

Periodic reference performance tests are used in this study to quantify BESS degradation [24]. Each test period's capacity is calculated using the total discharged energy measured at the AC interface and normalized to the baseline reference of the first RPT year's discharged energy. The normalized capacity at each year, t, is expressed as:

$$C_{\text{norm}}(t) = \frac{E_{\text{dis,AC}}(t)}{E_{\text{dis,AC}}(t_0)} \times 100, \tag{3}$$

where $E_{\text{dis,AC}}(t)$ is the discharged energy during the RPT at year t, and $E_{\text{dis,AC}}(t_0)$ is the discharged energy measured during the baseline RPT year.

To quantify the year-to-year variation in performance loss, the degradation rate was computed as the temporal derivative of the normalized capacity:

$$D_{\text{rate}}(t) = \frac{dC_{\text{norm}}(t)}{dt}, \tag{4}$$

where $D_{\text{rate}}(t)$ represents the annual rate of degradation in percent per year (%/yr).

TABLE 5. Summary of reference performance tests for the EW brown battery energy storage system.

Test Date	Discharge Power (AC) [kW]	Discharged Energy (AC) [kWh]	Average Container Temperature [°C]
11–07–2018	999	1,546.90	17.67
12–16–2018	999	1,563.53	21.53
04–16–2020	999	1,563.53	21.08
10–19–2020	999	1,530.27	18.99
06–01–2021	999	1,447.10	18.17
01–22–2021	999	1,513.63	15.87
11–23–2021	999	1,497.00	16.92
07–09–2022	999	1,447.10	13.65
02–28–2022	999	1,463.73	16.66
10–06–2022	999	1,430.47	14.64
11–14–2022	999	1,463.73	14.84
06–27–2023	999	1,397.20	14.09
12–16–2024	999	1,346.06	15.38
01–14–2025	999	1,347.30	15.50

Compared to the first-year baseline, the battery's normalized capacity shows a slow but steady decrease in usable energy output from 2018 to 2025, as illustrated in Fig. 8. During the first phase (2018-2020), the capacity stays relatively constant, which is in line with the early stabilization behavior commonly observed in utility-scale lithium-ion systems [29].

The degradation rate increases between 2020 and 2021, as demonstrated by a steeper capacity decline slope in Fig. 8. Increased depth-of-discharge operation, cycling stress, or operating temperatures may be the reasons for this accelerated aging regime. The degradation profile exhibits a more linear and moderate trajectory after 2021, indicating a change from the initial transient degradation phase to a steady-state aging regime [30]. As depicted in Fig. 8, total capacity loss approaches 13% by the end of 2025.

The corresponding annual degradation rate presented in Table 4 shows the year-to-year percent change in normalized capacity. A steep drop, approximately 4%, is observed between 2020 and 2021, aligning with the frequent cycling activities during this period as demonstrated in Fig. 2. This is followed by a gradual degradation rate and a stabilized phase, consistent with operational adjustments (reduced power dispatch and narrower SOC window) during the period.

VII. FIELD TESTING AND OPERATION PRACTICES

Field testing of battery energy storage systems provides critical insights into system performance, degradation behavior, and operational efficiency under field conditions. Through controlled charge–discharge cycles, rest periods, and standardized state-of-charge and power limits, field tests enable consistent tracking of capacity fade, round-trip efficiency, and thermal stability over time. Data obtained from these tests support validation of system models, calibration of degradation trends, and optimization of

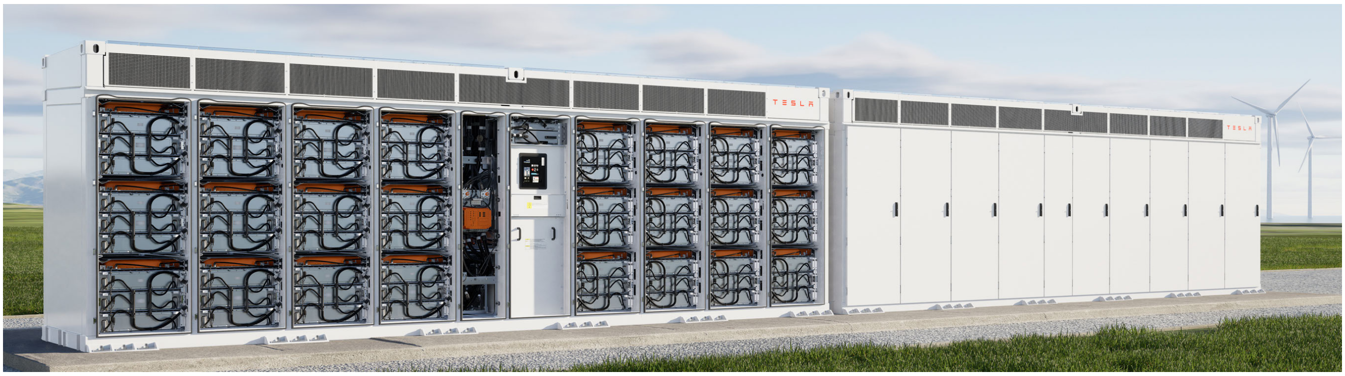


FIGURE 11. The Tesla Megapack 2XL exemplifies modern modular BESS, offering a containerized design with built-in battery modules, thermal management system, integrated power conversion units, and centralized control systems for large-scale utility projects. Its modular design allows flexible scaling for multi-megawatt installations. Image courtesy of Tesla, Inc.

dispatch strategies. Systematic field testing ensures operation within safe and efficient limits while establishing reliable benchmarks for long-term performance evaluation.

The EPRI Energy Storage Test Manual, developed under the Energy Storage Integration Council (ESIC), provides a standardized procedure for conducting Reference Performance Tests to monitor field-deployed battery system performance over time [24]. As illustrated in Fig. 9, the RPT protocol involves fully charging the system to its maximum allowable SOC, as defined by the manufacturer, followed by a short rest period of about 20mins. The system is then discharged at full power down to its minimum SOC limit, after which a brief rest period of approximately 5 minutes is observed. This is followed by a return to full charge and a final rest period of about 20mins. to complete the test cycle.

During each RPT, key parameters such as energy and duration for both discharge and charge cycles, and any BMS-imposed curtailment are recorded. Tests are recommended to be performed at regular intervals, typically quarterly, to create a consistent time series for performance tracking. For systems co-located with solar PV, RPTs are scheduled so that the charge cycle completes before sunrise and the discharge begins after sunset to avoid interference from PV generation. A critical aspect of the protocol is the use of consistent SOC bounds across all test events, enabling valid capacity normalization and degradation analysis.

The EPRI test protocol was systematically applied to the BESS to assess its operational efficiency and long-term performance under controlled field conditions. A summary of RPTs conducted at rated discharge power is provided in Table 5, capturing test dates, discharged energy, and average container temperature.

An example implementation of the reference performance test protocol on the E.W. Brown utility-scale Li-ion BESS is illustrated in Fig. 10. The test begins with a full charge to approximately 90% SOC, followed by immediate discharge at full power to the manufacturer's recommended minimum SOC limit of 10%. The battery is then recharged to its upper SOC bound (90%). This continuous cycle captures the system's charge and discharge energy under peak power conditions, enabling evaluation of round-trip efficiency and estimation of battery degradation.

Experimental field data demonstrate that battery energy storage system performance metrics and degradation trajectories are strongly dependent on operational parameters, particularly state-of-charge. As presented in EPRI's insights on BESS failure incident database [4] and corroborated by large-scale incident analyses in South Korea [25], maintaining appropriate SOC limits is central to fire prevention and system longevity. Statistical analysis of the failure incident database indicates that more than 70% of thermal incidents occurred at or near full charge states, where electrochemical instabilities, gas generation, and localized thermal excursions create favorable conditions for internal short circuit formation and subsequent thermal runaway propagation.

Consequently, the SOC operating range of the BESS was conservatively restricted to 35–65% to prioritize system safety and thermal stability under real-world conditions. This narrowed operational window may mitigate the elevated thermal risk associated with high SOC levels, particularly above 95%, and aggressive charge-discharge cycling. By constraining operation within this controlled electrochemical regime, the system may reduce exposure to the instability mechanisms identified in incident analyses, thereby potentially minimizing thermal stress and degradation rates. This precautionary approach, aligned with ESIC safety guidance, represents a performance-informed tradeoff between operational capacity and risk mitigation.

VIII. REVIEW OF TECHNOLOGICAL EVOLUTION IN BATTERY ENERGY STORAGE SYSTEMS

The technological evolution of utility-scale battery energy storage systems has been driven by significant advancements in subsystems such as the power conversion system, battery management system, and thermal management system (TMS). Together, these developments have transformed BESS from static energy storage devices into smart, grid-interactive infrastructures capable of providing essential services such as peak demand shaving, voltage stabilization, frequency regulation, and synthetic inertia support [31], [32].

Early BESS installations in the 1980s–1990s employed thyristor-based converters adapted from uninterruptible power supply systems, operating in grid-following mode without bidirectional control [33]. A significant transition in the 2000s was the transition to insulated-gate bipolar transistor (IGBT) voltage-source converters (VSCs), which allowed for bidirectional operation and four-quadrant active–reactive power control through pulse-width modulation [34], [35]. The 2010s were dominated by modular and multilevel topologies that enhanced redundancy, harmonic quality, and voltage scalability, such as cascaded H-bridge (CHB) and modular multilevel converter. Concurrently, wide-bandgap devices, particularly silicon carbide (SiC) MOSFETs, enhanced switching frequency, reduced losses, and enabled compact containerized designs [36], [37].

In order to provide synthetic inertia, voltage support, and black start functionality, which are essential for high-renewable-penetration low inertia power systems, the 2020s introduced grid-forming inverter (GFM) control, in which converters autonomously establish voltage and frequency references [38], [39]. Distributed submodule topologies established modularity as a central design feature, providing fault-tolerant operation and localized state-of-charge management [40]. Hybrid modular configurations integrate storage elements directly within converter submodules, enhancing transient response and reducing interconnection losses [41]. Multi-port modular converters further expand flexibility by linking multiple AC/DC interfaces in hybrid renewable–storage environments [42]. Although such systems present control complexity and voltage-balancing challenges, they represent the scalable foundation of next-generation grid-forming BESS [43].

Further advancement in power converter system design is the reconfigurable BESS, which facilitates the isolation of faulty cells from the system and allows fine power control of individual cells toward optimal system-level performance [44], [45]. Building upon this architecture, Farakhor et al. developed an optimal power management approach to minimize the total power losses during charging/discharging operations, while dispatching power in line with each cell's state to achieve SOC and temperature balancing [46].

Thermal management may serve as a critical factor influencing the performance, safety, and lifespan of BESS installations. From the 1980s through the 2010s, forced-air cooling systems were widely adopted due to their simplicity and cost-effectiveness. These systems may exhibit limited thermal uniformity and inadequate heat dissipation at high C-rates, which could adversely affect system reliability and operational efficiency [47], [48], [49].

Research throughout the 2010s demonstrated the increased performance of liquid cooling, particularly in high-power and large-scale applications, due to its superior heat transfer capability and enhanced temperature uniformity compared to air cooling. Advanced liquid cooling architectures, including direct liquid cooling and immersion-based systems, further reduce thermal resistance and enable improved thermal runaway mitigation [50], [51].

More advanced designs now incorporate hybrid thermal architectures that combine liquid cooling with phase change materials (PCMs) or immersion cooling for superior transient thermal buffering and thermal-runaway mitigation [52], [53]. Pioneering studies by Al-Hallaj and Selman [48] established PCM's latent heat absorption capability for moderating cell temperature spikes, while recent works demonstrate liquid–PCM composites enhancing both steady-state cooling and safety margins [49], [54], [55]. Heat-pipe and thermosyphon systems have been investigated as passive two-phase complements to liquid cooling for high-heat-flux cells, further improving thermal uniformity and system resilience. These hybrid strategies now represent the state of the art for thermal safety and performance optimization in utility-scale battery energy storage systems.

Battery management systems for large-scale BESS have evolved from centralized supervisory units toward distributed and hierarchical architectures to address scalability, reliability, and fault isolation as battery pack sizes and parallel string counts increase [56], [57]. Early distributed BMS designs introduced modular cell- and module-level monitoring units interconnected via Controller Area Network (CAN) buses, enabling improved fault localization, redundancy, and maintainability in multi-rack battery systems [58]. To overcome the inherent limitations of distributed coordination, hierarchical BMS architectures decouple time-critical operations from higher-level supervisory functions, including system-wide optimization [59].

Recent advances in BMS research reflect a paradigm shift toward software-centric and cyber-physical architectures, integrating advanced battery modeling, predictive degradation analytics, and digital twin frameworks to enable long-term asset management and adaptive control strategies [60], [61]. Contemporary BESS architectures increasingly utilize cloud-based connectivity and fleet-level data aggregation to facilitate SOH monitoring, remaining useful life estimation, and coordinated dispatch of geographically distributed energy storage assets [62]. Furthermore, AI-enabled digital twin architectures have been shown to support real-time health estimation and degradation-aware control, achieving high prediction accuracy while enabling adaptive charging strategies to mitigate aging mechanisms [63].

The integration of modular converter topologies, hybrid liquid–PCM thermal systems, and advanced BMS architectures defines the state of the art in utility-scale BESS. These technologies underpin the flexibility, resilience, and stability requirements of modern renewable-intensive, low-inertia grids [64], [65].

In the context of recent technological advancements in utility-scale BESS, Tesla's Megapack 2XL, shown in Fig. 11, exemplifies an integrated and modular BESS architecture. The Megapack 2XL is a factory-assembled, pre-tested system configurable in standard two-hour and four-hour durations, delivering nominal AC power up to 1.9 MW with energy capacity on the order of 3.9 MWh per unit at 480V AC.

In contrast to conventional containerized BESS deployed as fixed-capacity assets, the modular architecture of this system permits future battery capacity augmentation without requiring redesign of the PCS. Power conversion is realized through integrated bidirectional inverters that support grid-responsive operation, including real and reactive power control, while achieving reported round-trip efficiencies in the range of 92–94%. These efficiency values account for auxiliary and thermal management system losses. Cooling in the Megapack 2XL is provided by an active liquid thermal management system circulating a 50/50 ethylene glycol–water mixture through the battery and power electronics.

IX. DISCUSSION

Publicly available field data from utility-scale lithium-ion BESS remain scarce, particularly long-term, high-resolution datasets that are essential for informing operational strategies, safety protocols, and reliability assessments. Within this context, the BESS at the PPL Renewable Integration Research Facility constitutes a rare resource, providing long-term, high-resolution field data.

The facility enables public access to real-time operational data and shares comprehensive datasets with national laboratories, including EPRI, thereby facilitating independent analysis over extended periods. Most importantly, the facility has served as a platform for safety-focused research, the development and validation of safety-related operational practices, and the training of engineering students using real-world utility-scale BESS data and systems.

The performance characteristics analyzed of the field pilot unit are consistent with the technological maturity of utility-scale BESS at the time of deployment. As reported in literature, early systems were commonly configured using loosely integrated subsystems, with components such as the power conversion system sourced from external vendors and integrated with site-level controls. At the E.W. Brown facility, the reliance on forced-air thermal management, together with limited integration between the PCS, control, and thermal systems, contributed to extended unplanned outages. These shortcomings have been addressed in modern BESS through integrated, modular architectures that improve thermal coordination, system integration, and availability.

Operational experience reveals fundamental trade-offs between safety and efficiency in utility-scale BESS deployments. Constraining the allowable SOC operating window may effectively enhance safe operation but concurrently reduces energy availability and overall system efficiency. This limitation is compounded by reduced PCS efficiency under partial-load operation, demonstrating how safety-driven operating strategies and inverter performance characteristics collectively influence deliverable energy in grid-scale BESS.

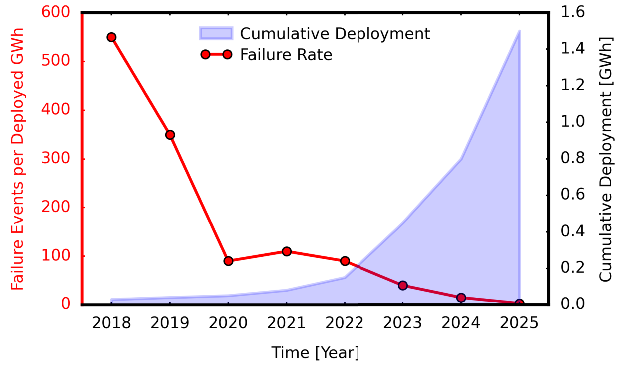


FIGURE 12. Historic evolution of battery deployment and failures based on the data reported in [66]. In line with typical expectations, the fault rates reduced as technology evolved and new solutions and products were developed and implemented.

Analysis of long-term operational data establishes a correlation between system disturbances and ambient temperature, indicating that thermal conditions influence BESS reliability and availability. This observation reinforces the need to incorporate climate and site-specific thermal conditions into BESS deployment decisions, enclosure design, thermal management system sizing, and operational planning.

The declining failure rate observed in grid-scale BESS in recent years, despite rapid deployment growth as evidenced in Fig. 12, reflects progressive improvements in system reliability. Notably, failure events per deployed GWh declined sharply from about 550 in 2018 to near negligible levels by 2025, despite cumulative deployed capacity growing substantially over the same period [66]. This trend may be largely attributed to technological advancements in critical subsystems, particularly thermal management, power conversion, and battery management systems.

Elevated fault rates during early deployment phases are consistent with established technology maturity patterns. In this context, the unplanned outage analysis of the pilot unit examined in this work is representative of the technology of its era, with identified failure modes concentrated in the thermal management system, power electronics conversion system, and BMS. These results reflect the operational limitations of earlier-generation BESS and reinforce the significance of subsystem advancement in improving reliability.

X. CONCLUSION

This work presented an analysis of the long-term operation of a 1MW / 2MWh utility-scale Battery Energy Storage System field pilot unit located at the PPL Renewable Integration Research Facility. Commissioned in 2017, the facility has operated continuously as a research platform for evaluating battery operational strategies, safety practices, and system behavior under real-world grid and environmental conditions. Over its nine year operational lifetime, the BESS at the site has supported collaborative research with academic institutions and national laboratories by sharing high resolution cell-level data. It has also served as a training and knowledge-transfer venue for students, battery operators, and visiting researchers from around the world who are applying lessons learned at this facility to new BESS.

Using a long-term high-resolution operational dataset, which has been made publicly available, this study quantified performance and reliability metrics, including DC and AC round-trip efficiency, degradation rate, normalized capacity loss, and system availability. The system recorded AC RTE ranging from 87% - 90% across the years, with a total capacity loss approaching 13% by the end of 2025. A shift from reactive downtime response to proactive, reliability focused, and safety-oriented operational practices is observed from the operational and outage analysis, with an up-time of approximately 96% in 2025.

This work analyzed the outage characteristics observed over the long term operation of a large-scale grid-connected battery energy storage system, identifying faults that are specific to the technology of its era. A systematic review of BESS technological evolution is then presented, demonstrating that reliability improvements have been concentrated at the subsystem level, which is consistent with the fault characteristics identified and reported in this study.

The operational experience gained from this pilot installation directly informed the design and operational strategy of the new 125MW/500MWh system under development at the research site. Collectively, these results highlight the value of sustained field pilots and transparent operational data in advancing the safety, reliability, and performance of modern utility-scale energy storage systems.

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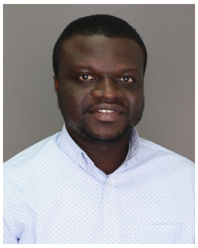

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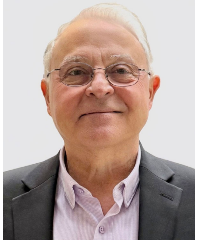

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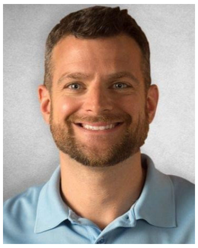

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