2024 TECHNICAL UPDATE

Assessing Energy Storage Degradation from Field Test Data

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ABSTRACT

Energy storage systems (ESS) are emerging as a major grid resource due to their flexibility and their ability to provide long duration/multi-day discharge support. There is a lack of widespread field data on how these energy storage technologies truly degrade over time. The asset degradation information is important to plan and operate the system effectively and efficiently. This report focuses on outlining standardized tests and analysis approaches to track and monitor the degradation of energy storage systems over the lifetime of the project. The goal is to be able to collect degradation information from field demonstration projects, which can help build a technology specific, energy storage degradation database. The availability of a large amount of field data can inform the planning and operation of future energy storage systems. EPRI, in concert with the Testing and Characterization Working Group of the Energy Storage Integration Council (ESIC), has developed several test plans for characterizing the energy storage operation. The test procedures in this report are largely based on an ESIC test manual with a focus on degradation of ESS in a grid connected system. This report also presents a case study on degradation tracking on an actual 1 MW/2 MWh E.W. Brown ESS, which is owned and operated by PPL Corporation and LG&E KU in Harrodsbug, Kentucky.

Keywords

Degradation
Energy storage
Energy storage system (ESS)
Operation
Planning

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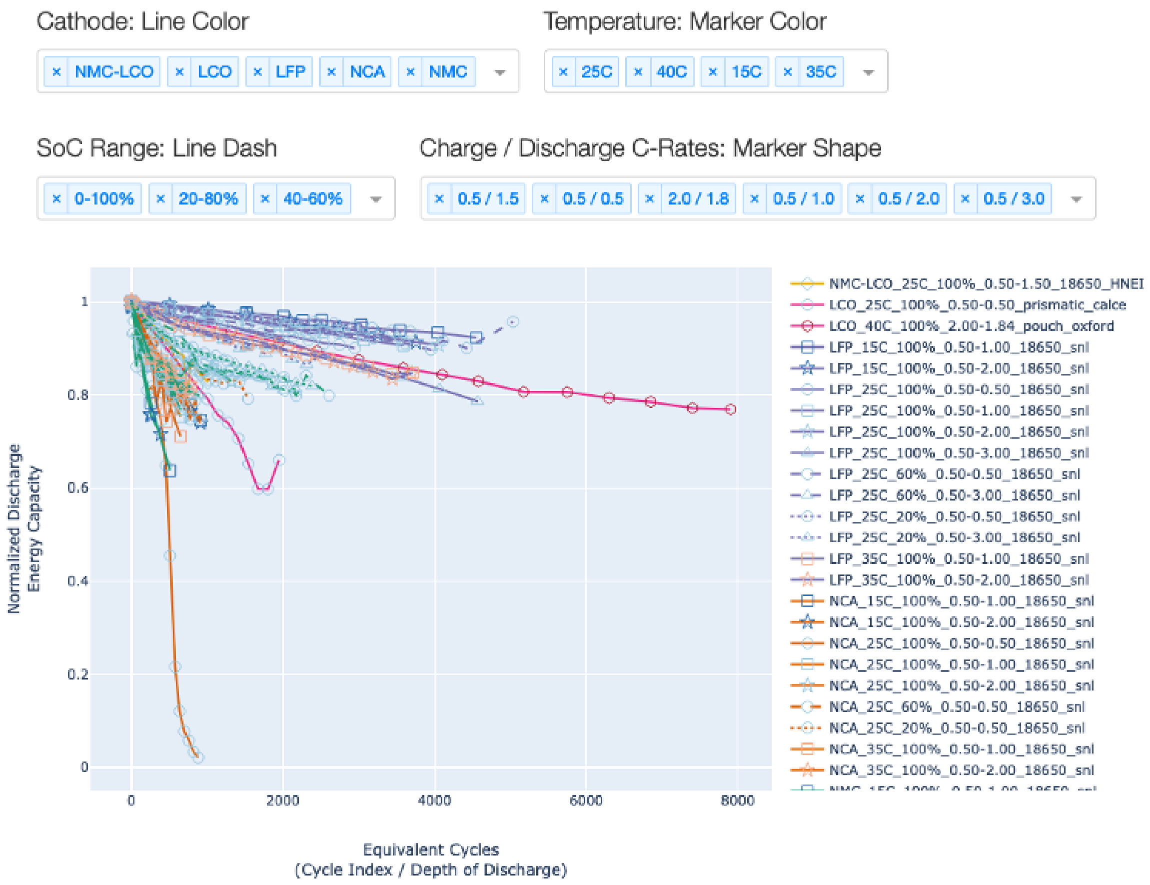
1 INTRODUCTION

Energy storage is increasingly being deployed in utility, residential, and commercial sectors. The range of use cases that the energy storage can address is expanding owing to its ability to stack services from grid and market value streams. Energy storage is deployed for microgrid applications to improve individual customer, and community resilience to extreme weather events and long-term utility power outages. Energy storage systems are also emerging as a major grid resource due to their rapid dispatchability to correct issues that might occur on the grid. There are also many government incentives and tax benefits to accelerate the growth of energy storage in electric power systems to meet corporate, state, and federal government deployment and decarbonization targets, and greenhouse gas-reduction goals.

There are a few publicly available data sets on energy storage degradation over time. Batteryarchive.org is a database that is hosted by Sandia National Laboratories on the long-term degradation of lithium ion cells due to environmental and operational conditions like ambient temperature, depth of discharge (DoD), and rate of discharge. This laboratory data is obtained by accelerated charge/discharge testing of single battery cells. EPRI has extracted degradation curves as shown in Figure 1 based on these cell-level testing data for Nickel Manganese Cobalt (NMC) lithium ion energy storage for various temperature, DoD, and discharge rates.



Cathode: Line Color: NMC-LCO, LCO, LFP, NCA, NMC

Temperature: Marker Color: 25C, 40C, 15C, 35C

SoC Range: Line Dash: 0-100%, 20-80%, 40-60%

Charge / Discharge C-Rates: Marker Shape: 0.5 / 1.5, 0.5 / 0.5, 2.0 / 1.8, 0.5 / 1.0, 0.5 / 2.0, 0.5 / 3.0

Figure 1. Example of a dashboard created with data from BatteryArchive.org to investigate how degradation is affected by variables like chemistry, cycling temperature, state-of-charge range, and C-rate. This graph is based on laboratory cycling data.

The experimental test data repository is good to understand basic trends of energy storage degradation, but there are caveats, for example these the tests are carried out in a controlled lab environment on a single cell. The results are specific to the combination of testing parameters including cell chemistry, temperature, and use-protocol. However, in actual field system, there is less control of the external factors, and the energy storage operation is not necessarily the same every day. The experimental cell level data are representative but do not inform how energy storage systems in the field will truly degrade over time.

Given the increase in energy storage deployments, knowing how energy storage degrades over time is of key importance in project planning and estimating net life cycle cost. There is a need for a data repository of existing real world energy storage systems. For consistent and meaningful results, it is important to have standardized test procedures and analysis approaches to evaluate and track the performance of energy storage system on the field. Additionally, rich data must be made available and collected at high resolution from the systems to ensure that proper analysis is possible. If a system vendor refuses to supply adequate data for analysis, this is a red flag that must be addressed before proceeding.
This report focuses on outlining a test plan to track and monitor degradation of energy storage

systems that is already deployed in field. The goal is to be able to collect degradation information from fielded storage projects, to help build a technology specific energy storage degradation database. Availability of large amounts of field data provides opportunities for analysis that can drive improved planning and operation of future energy storage systems.

2 REFERENCE PERFORMANCE TEST PROCEDURE

EPRI's Energy Storage Integration Council (ESIC), with input from a community of industry participants including utilities, energy storage suppliers, integrators, and research organizations, developed a reference test manual to support the consistent characterization of energy storage system performance and functionality[1]. The procedures outlined here for degradation tracking are based on ESIC's test manual. In addition, this section includes a modified test procedure for solar plus storage coupled systems.

General Test Procedures for Energy Storage Performance Tracking

In the last five years, there has been an increase in the number of megawatt (MW)-scale energy storage assets deployed in the field. Because electrochemical energy storage is a relatively new asset type in the 100-year-old power system grid, there is very little information of how these assets degrade over time. It is imperative that all the energy storage systems that are already deployed and being deployed in the future follow standardized test procedures to extract degradation information from these assets. The vision is to be able to use the test plan to create a large open-source field test data archive from actual energy storage systems that are deployed on-site.

The procedure outlined here is a full charge and discharge cycle to measure the total discharge capacity of energy storage. It is recommended that the tests are performed at regular intervals of time to track the degradation of energy storage assets over time. Figure 2 is a representative single line diagram where energy storage is the only asset, or the major asset, in the site where the testing is performed. Figure 3 is an illustrative example on the reference performance test.

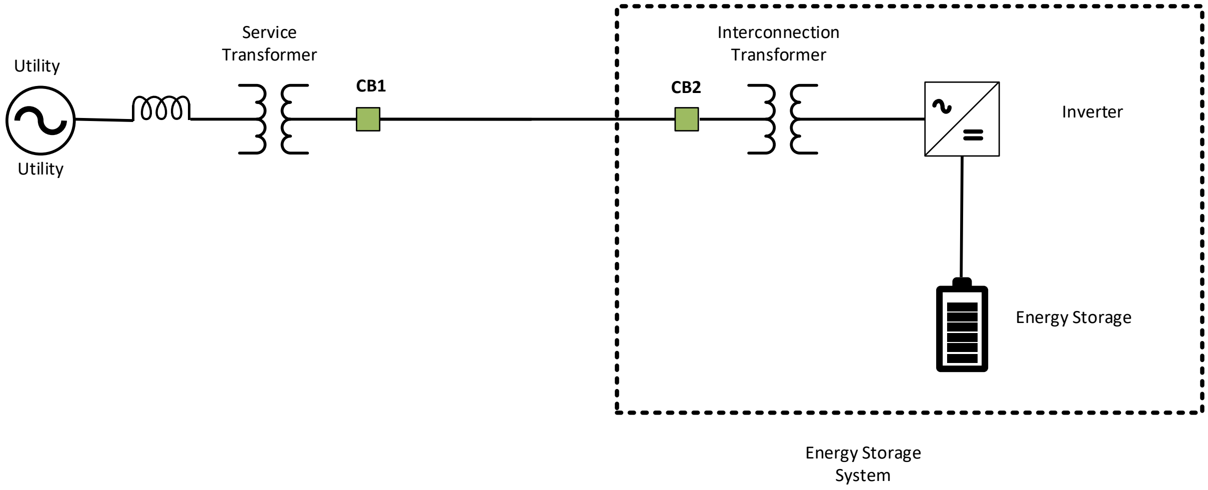


Figure 2. Single-line diagram showing the energy storage system under test.

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[1] Energy Storage Integration Council (ESIC) Energy Storage Test Manual.

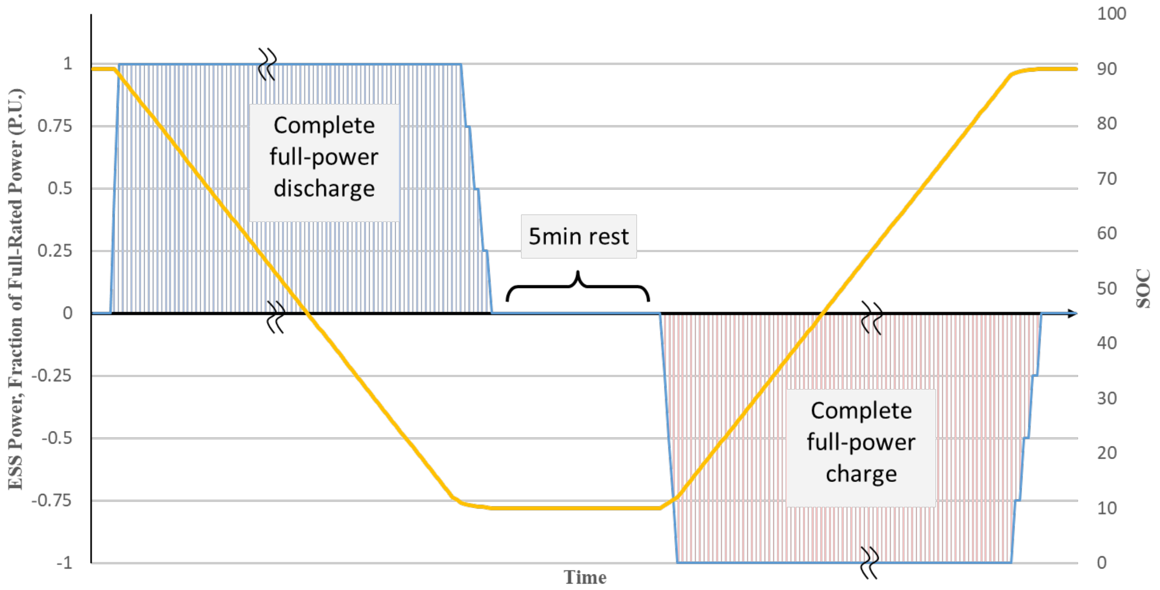

Figure 3. Example operation for this reference performance test.

Test Procedure

1. Charge the battery energy storage system (BESS) to maximum state of charge (SOC) as dictated by the battery management system (BMS) or warranty documentation (which might be < 100% SOC) using recommended charge power[2], allowing power to taper as dictated by BMS.
2. Rest for 20 minutes.
3. Discharge at rated power until it reaches its lower SOC limit as dictated by BMS or warranty requirements (which might be > 0% SOC).
4. Note that the BESS might disconnect automatically as low SOC limit is reached.
5. Rest for five minutes.
6. Charge the BESS to maximum SOC as dictated by BMS or warranty documentation using the recommended charge power, allowing power to taper as dictated by BMS.
7. **Note**: The BMS might curtail charge current as the BESS approaches full charge; document any curtailment as observed and consult with the BESS vendor to ensure this behavior is as intended.
8. Rest for 20 minutes.

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[2] It is assumed that the recommended charge power is equal to the rated power. If this is not the case, please adjust the charge duration.

Parameters Measured

1. **Delivered Discharge Energy, (E_D)**: This represents the energy delivered from the ESS to the facility/grid.
2. **Discharge Duration, (t_D)**: This represents the time required to actively deliver electric energy from the ESS, starting at maximum SOC and reaching the minimum SOC at rated continuous charge power. **Note** the power rating at which the energy is discharged.
3. **Charge Energy, (E_C)**: This represents the total energy delivered to the ESS from the external energy source.
4. **Charge Duration, (t_C)**: This represents the time required to actively deliver energy to ESS, starting at minimum SOC and reaching the maximum SOC at rated continuous charge power. **Note** the power rating at which the energy storage is charged.

Frequency of Testing and Timing

For maximum benefit this procedure should be performed approximately one time per quarter (every three months). The exact dates of the tests are up to the discretion of the asset owner and might be dependent upon exogenous factors like weather. However, the interval between tests should be as uniform as possible.

For behind-the-meter energy storage, the tests should be timed such that it does not create new peaks on the customer load, and it should be performed during off-peak tariff durations. For front-of-the-meter energy that is not subjected to utility tariff rates, the tests should be timed such that no new peaks are created at the distribution level transformer.

Figure 4 shows an example of an alternate current (AC) coupled solar plus storage system.

Alternate Test Procedures for Energy Storage Coupled with Solar

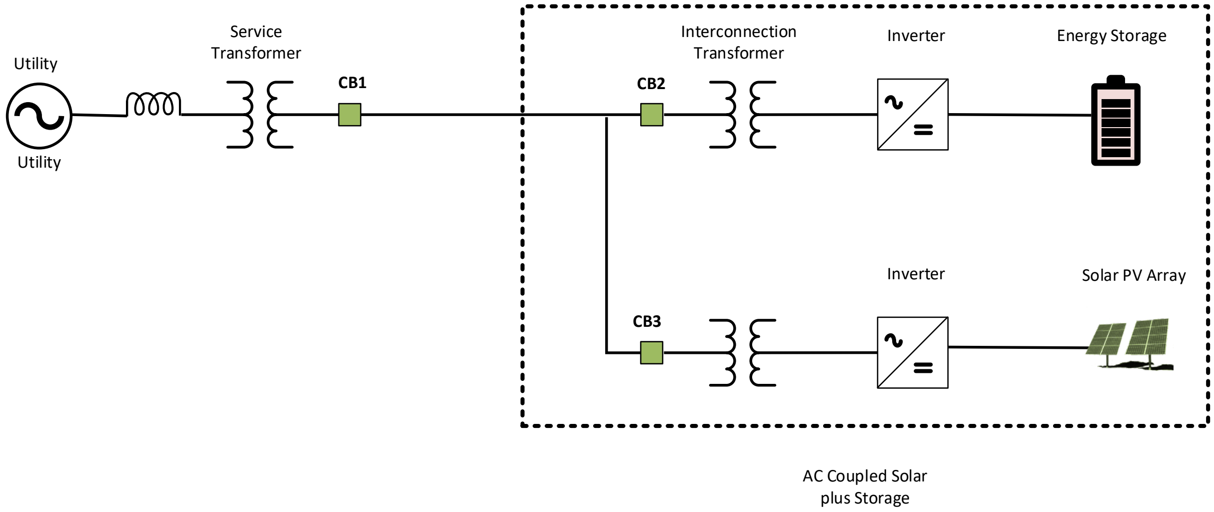

Figure 4. AC coupled solar plus storage system.

This is an alternate procedure for solar coupled storage systems. Figure 3 is an alternate current (AC) coupled solar plus storage system, but the procedure can be applied to DC coupled systems as well. An alternate procedure is needed because one must evaluate the performance of energy storage without solar power variability. Often, one of the major use cases of energy storage in solar plus storage systems is solar smoothing, and this function could interfere with the performance tests, which require continuous rated power charge and discharge from energy storage. Because the reference performance tests are executed at rated charge and discharge power, it might not be possible for the solar plus storage system to maintain the continuous rated charge and discharge power for the battery.

Frequency of Testing and Timing

The performance tests are also recommended to be repeated one-time every quarter. The timing for testing of the coupled system should ensure consistent power flow into and out of the battery during the reference performance tests (RPTs), charging and discharging should source or sink from/to the grid directly with little to no interaction from the solar generation. To achieve this, without curtailing solar generation, the two aspects that should be considered are: 1) full charging should be complete before sunrise and subsequent full discharge should not start until after sunset; and 2) testing should be planned to begin on a day with forecasted sunny weather.

After planning for and accommodating these considerations, the test procedures might commence as shown below.

Conditions

Testing should start early enough such that charging cycle is complete at least 15 minutes (min) before sunrise, that is, the testing should start before charging time (t_C) + 15 mins before sunrise. The discharging cycle should start after the sun is set. Figure 1 shows a hypothetical day of testing. Figure 5 shows a simplified sketch of the testing operations on a sunny day for 1.5 MW/6 MWh energy storage system.

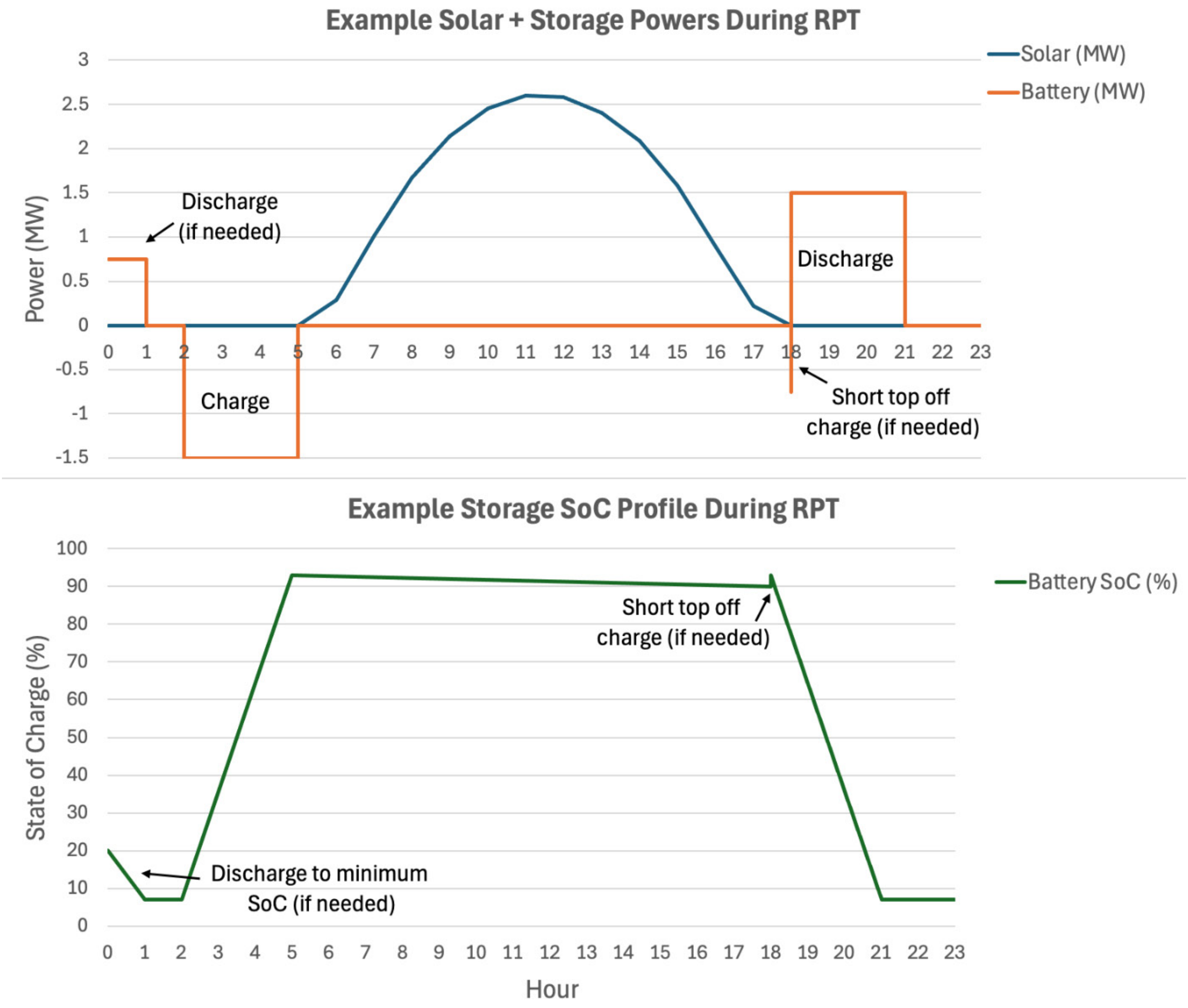

Figure 5. A simplified sketch of the testing operations on a sunny day for 1.5 MW/6 MWh energy storage system. The sunrise and sunset times shown here represent expected local times for testing in early September and will vary throughout the year.

Procedure Steps

1. Ensure that the SOC of the system reaches minimum SOC before the expected charge duration, (t_C + 30 min) to sunrise.
2. Let the system rest (zero power command) for at least 15 min at the min SOC.
3. Allowing sufficient time before sunrise initiate a full power charge to bring the system to its maximum allowed SOC. Ensure that there are at least 15 min after reaching its full SOC.
4. Stop the charge when the system is at its maximum SOC.
5. Put the system into an operating mode, which prevents the operation of the battery. Between sunrise and sunset, allow the battery to remain idle. Generation from the solar plant should be directed to the grid and not the battery.

6. Check the battery's SOC 15 min after sunset. if it has dropped below its maximum SOC then initiate a short, half-power "top off" charge to until the system reaches its maximum allowable SOC.
7. If a top off charge was needed, then rest the battery for 15 min.
8. Start a full rated power discharge until it reaches its minimum SOC percent.
9. With the test complete, the battery system might now resume with normal operation.

Analysis

The analysis described in this section is applicable to both the general and the solar coupled energy storage systems. For each reference performance test event, the following information needs to be extracted from the tests: 1) Test date and time, and 2) minimum and maximum SOC percent for the discharge cycle.

Ensure that the energy storage discharges at rated power, during the entire discharge cycle.

After all the information is extracted from the available reference performance tests (RPTs), a set of common SOC bounds to apply to all events must to be chosen to ensure degradation of a common SOC range is analyzed across the system's life. Table 1 is a sample degradation tracking worksheet with three sample quarterly RPTs with individual SOC boundaries of 10%–80%, 11%–80%, and 10%–85%. The common SOC bound for all three events is 11%–80%. Discharge capacity (kWh) for all three tests for the shared SOC bound of 11–80% is calculated from each event's. Finally, SOH is estimated by normalized the discharge capacities based on the first recorded discharge capacity.

Table 1 shows a sample degradation tracking worksheet.

Table 1. Sample degradation tracking worksheet.

RPT Date and Time	Minimum and Maximum % SOC Recorded	Common SOC Bounds %	Discharge Energy Capacity for Common SOC Bounds (kWh)	State of Health
January 2024	10%–80%	11%–80%	X1	X1/X1 = 1
March 2024	11%–80%		X2	X2/X1
June 2024	10%–85%		X3	X3/X1

Using the state of health (SOH) values and Δ SOH variation between the two-test instance, the degradation curve for each energy storage can be plotted. The degradation rate gives an idea on the remaining life of the battery asset. If the degradation rate is higher than expected, then it should trigger additional investigation to do corrective action to improve the life of the asset.

In addition to energy storage degradation, it is possible to extract the following metrics from the reference performance tests. More detail can be in the ESIC *Energy Storage Test Manual*.

- Round trip efficiency
- Charge and discharge energy capacity
- Charge and discharge duration
- Auxiliary load
- Standby losses

3 CASE STUDY FROM A REAL FIELD SYSTEM

This section will cover a case study from applying this energy storage degradation tracking methodology to a real field system over many years.

Site and Battery Energy Storage System (BESS) Description

The battery system in this case study is a 1 MW/2 megawatt-hours (MWh) E.W. Brown BESS, which is owned and operated by PPL Corporation and LG&E and KU, co-located within the E.W. Brown Generating Station in Harrodsburg, Kentucky.

Table 2. PPL Corporation's E.W. Brown system's characteristics.

System Name/Alias	Size	Current State	Location	Technology
E.W. Brown BESS	1 MW, 2 MWh	Research system, operational since late 2016	Harrodsburg, Kentucky	Li-ion (NMC) – LG Chem Ltd.

The data received from this system are a robust, long-term energy storage dataset with over 1,000 data points at one-second resolution for a seven-year period[3]. A snapshot on the operational data for the entire seven-year period is included in Figure 3. The data from this system was collected nearly continuously, and periodic reference performance tests were performed roughly one time every six months.

As part of EPRI's performance and reliability foresight initiative, EPRI has performed a variety of analyses on the operational test data to track metrics like round-trip efficiency, degradation, standby losses over time, cell balancing and its impacts on standby losses, and differential voltage trends.

This data was used to track degradation trends over time. This section will describe the analysis methodology and compare the independently calculated SOH to the SOH reported by BESS's BMS.

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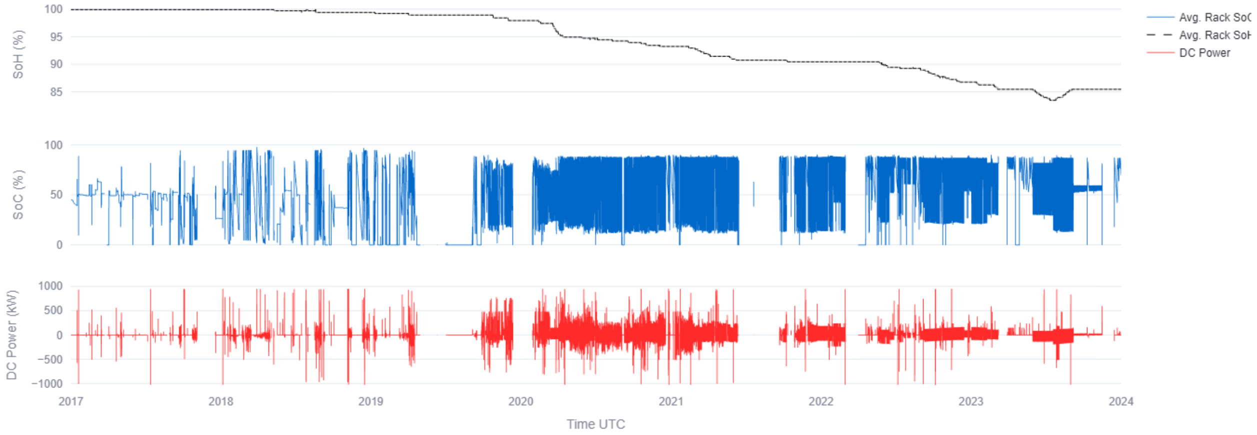
[3] Data courtesy: Thanks to the research team at LG&E and KU, and PPL Corporation for providing data over the years.

Figure 6 shows PPL Corporation’s E.W Brown historical operational data for seven years with reported battery BMS and reported SOH.



Data courtesy of PPL Corporation.

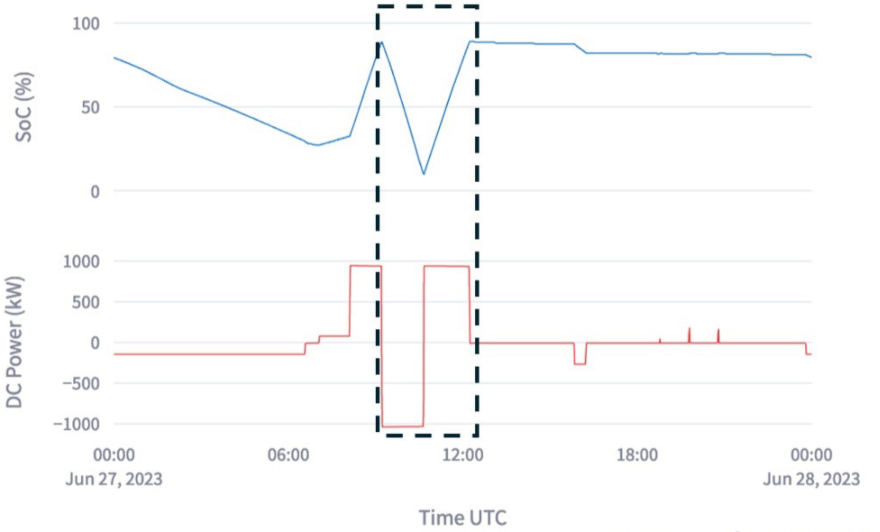
Figure 6. PPL Corporation’s E.W Brown historical operational data for seven years with reported battery BMS and reported SOH.

Reference Performance Tests

For this system, the reference performance tests have a few notable deviations from the procedures described previously. There were no rests between the half cycles but, for the sake of consistency, this reference performance test remained unchanged throughout the seven years of operation. Where the minimum SOC was generally 10%, and maximum SOC was 90% the reference performance tests for this system generally consisted of the following:

- Full power charge to maximum SOC
- Full power discharge to the minimum allowed SOC (discharge half-cycle)
- Full power charge up back to maximum SOC (charge half-cycle)

Figure 7 shows one of the reference performance tests performed on the system on June 27, 2023. The dashed lines show the SOC increase to 90% at rated charge and drop down to 0% SOC, and then back again to maximum SOC. The test was completed in less than six hours for the 2 MWh system.



Data courtesy of PPL Corporation.

Figure 7. A sample reference performance test carried out on June 27, 2023.

Degradation and State of Health (SOH) Calculations

For each reference performance test event, metadata for the discharge half cycle (for example, start time, end time, minimum SOC, maximum SOC, and so on) is extracted. This information is used to compare all discharge events and create a common basis for contrasting all discharge events over time. Before calculating the discharge energy capacity of each event independently, all events are compared to find a common SOC window upon which to filter each event's data to ensure the comparison of energy values over a common SOC range. For this system, the common window was 11%–89% SOC because there were some events where the SOC did not reach the normal minimum or maximum SOC, so all events were narrowed before acquiring energy capacity values.

In this example, the discharge energy capacity values are normalized using the first test's energy capacity to convert the data to something more akin to reported state of health.

Figure 8 shows a comparison of the normalized discharge energy capacity over time as calculated using periodic RPTs performed on this system.

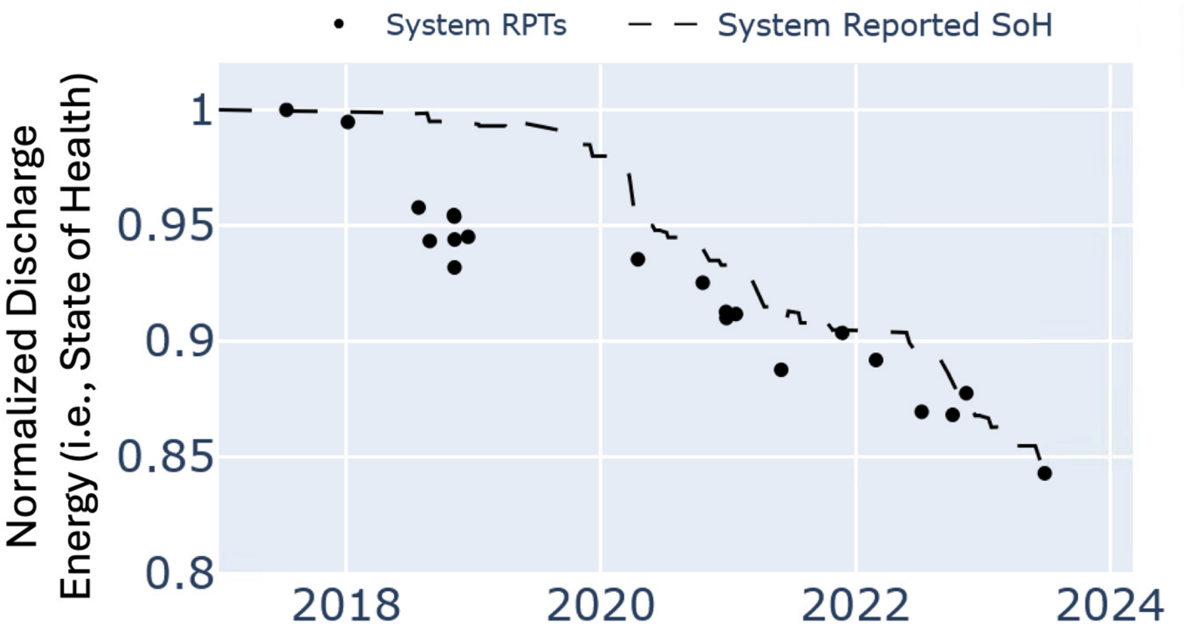


Figure 8. A comparison of the normalized discharge energy capacity (that is, state of health) over time as calculated using periodic RPTs performed on this system (that is, dots). The dashed line shows this system’s internally calculated and reported state of health over time. Special thanks to PPL Corporation for providing the original system data. **Note**: The firmware was changed around 2020, in part due to the BMS reported SOH not following measurements, as observed in the portion of the chart before 2020.

Table 3. Degradation tracking for PPL Corporation's E.W. Brown system.

RPT Date	Normalized SOC bounds %	Normalized Discharge Energy Capacity (kWh)	State of Health
7/13/2017	11%–89%	1690.684138	1
1/5/2018		1681.78175	0.994734
7/27/2018		1619.309611	0.957784
8/28/2018		1594.993417	0.943401
11/5/2018		1613.954458	0.954616
11/7/2018		1612.677209	0.953861
11/7/2018		1575.668138	0.931971
11/7/2018		1596.12761	0.944072
12/16/2018		1597.988902	0.945173
4/16/2020		1581.60814	0.935484
10/19/2020		1564.543973	0.925391
12/25/2020		1543.261305	0.912803
12/26/2020		1538.757471	0.910139
1/22/2021		1541.539223	0.911784
6/1/2021		1501.065779	0.887845
11/23/2021		1527.932944	0.903736
2/28/2022		1508.176251	0.892051
7/9/2022		1470.265805	0.869628
10/6/2022		1468.132111	0.868366
11/14/2022		1483.892055	0.877687
6/27/2023		1425.370111	0.843073

Interpretation and Discussion

This Case Study shows the importance of independent energy storage degradation tracking as the reported SOH values from BMS is often not transparent, and there is little to no explanation on how these values are computed.

Calculating these values independently can help validate the reported values and provide a clearer picture of battery degradation over time. For example, Figure 5 shows the calculated versus reported SOH values. It can be observed that even after normalizing the first test value, there is 5% deviation between the calculated and reported values during the 2018–2020 timeframe. The gap significantly decreased around 2020. This change also coincides with potential firmware alterations that happened around the year 2020. The latest value calculated in 2023 is 84%, which is very close to the reported SOH%. After the software version 1.3.1 was implemented in 2020, it can be observed there is an immediate 5% drop in the reported SOH values. This suggests that the firmware upgrade might have recalibrated the SOH estimation. This again emphasizes the importance of independent degradation tracking.

Figure 9 shows the correlation between firmware version updates and reported SOH values.

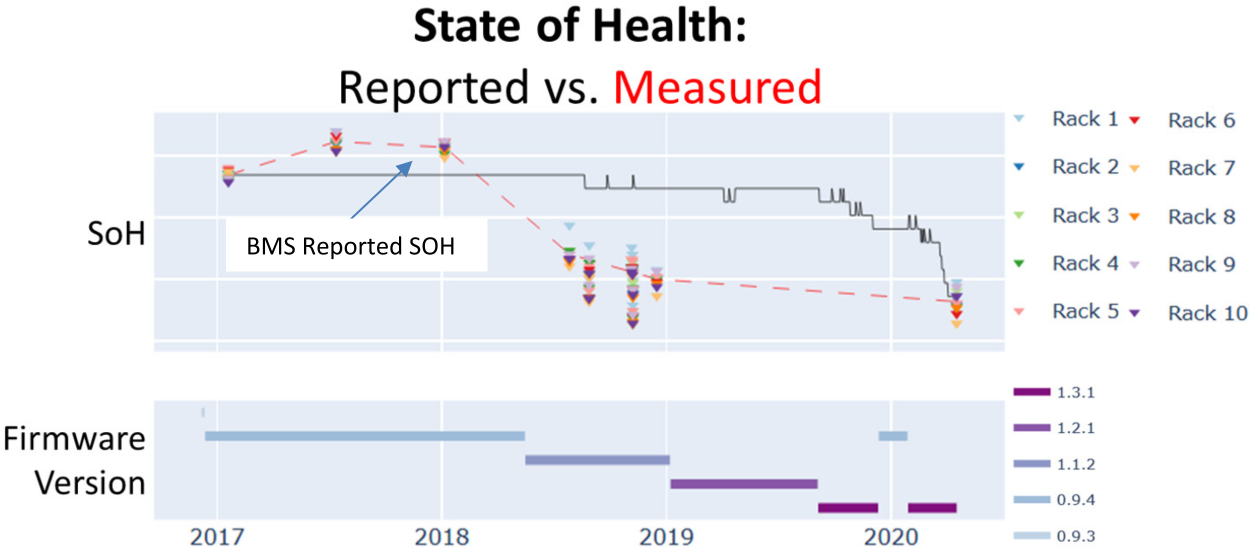


Figure 9. Correlation between firmware version updates and reported SOH values.

4 CONCLUSION

The economic viability of a proposed energy storage system depends heavily on its forecasted lifetime, throughput, and calendar life. Availability of very detailed data to model degradation rates in variable real-world conditions is presently lacking. However, this report describes a methodology to capture such data which, if cataloged, could provide improved means for those procuring storage to more accurately forecast the lifetime and economics of a proposed system. As well, this could inform optimal design decisions, including—but not limited to—sizing, SOC limits, available use cases, augmentation planning, pricing, climate control design and setpoints, and so on.

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