Field-Aging Test Bed for Behind-the-Meter PV + Energy Storage

Preprint

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National Renewable Energy Laboratory

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***Abstract* — Small DC-coupled battery test systems are deployed at the National Renewable Energy Laboratory to evaluate capacity fade models and report on performance parameters such as round-trip efficiency under indoor and outdoor deployment scenarios. Initial commercial battery products include LG Chem RESU lithium-ion (Li-ion) and Avalon vanadium redox flow batteries. Adapting indoor lab-scale test methods to outdoor systems has challenges, including maintaining constant temperature and fully controlling batteries through standard discharge curves. Initial measurements show the Li-ion battery systems performing within expectations, near 85% round-trip efficiency. Initial lifetime modeling and measurements indicate that battery capacity could degrade by 20%–35% over 10 years at current rates.**

I. Introduction

Battery energy storage systems (BESS) are increasingly used in the electric grid to minimize the impact of variable power generated by renewable energy sources and to shift renewable generation to coincide with electricity demand. Utilities are starting to transition away from net metering policies toward time-of-use and demand-based rate structures that favor the integration of BESS with photovoltaics (PV). This is particularly the case for localities where the export of renewable energy is prohibited [1], [2]. Battery energy storage might also increase facility resilience if configured to provide backup power during grid outages [3].

Battery lifetime has a critical impact on project levelized cost of energy (LCOE) [4], [5], with the intended use case of the battery influencing both the longevity of the battery and design specifications, such as the ratio of power to energy for the battery [6]. The most economic choice for a project might, in fact, be the one with the higher up-front cost (e.g., vanadium redox flow batteries) if the longer operational lifetime warrants the increased initial investment [7]. Being able to meet a typical 10-year warranty period under field conditions is also important for lithium-ion (Li-ion) batteries because the economic payback period can be at least this long for some cases of behind-the-meter deployment [8]. It is therefore critical to be able to accurately assess the state of health (SOH) of fielded battery systems and to predict the longevity of future battery + PV installations.

TABLE I. Battery Systems Currently Under Test

Model	Chemistry	Deployment	SOC Range	Qty
LG RESU7H	Li-ion NMC	Outdoor	15%–100%	1
LG RESU7H	Li-ion NMC	Indoor	15%–100%	2
Avalon AFB 2.10	Vanadium redox flow	Outdoor	0%–100%	2

The current state of knowledge of battery system lifetime and capacity degradation is determined in part from indoor accelerated testing [9], [10] and physics-of-failure models of battery lifetime [11]; however, there is no substitute for field experience and validation under actual grid-interactive conditions. In this paper, we describe a field test designed to:

- Evaluate commercial BESS products for lifetime, efficiency, and operational capability
- Validate existing battery lifetime models under a variety of environmental and use cases
- Identify gaps in standards and measurement methods for fielded PV + BESS.

Our test bed currently comprises three residential-scale Li-ion batteries and two vanadium redox flow batteries (Table I), with another 50 kWh of commercial products under consideration. Batteries are DC-coupled through hybrid PV inverters in a ratio P_{Batt} / P_{PV} 2-4h (approx.) and programmed to shift the daytime PV production into the late afternoon, assuming the scenario of updated utility time-of-use rates [12]. Environmental conditions and use conditions vary to reflect the different deployment options of typical residential behind-the-meter battery systems, including outdoor unconditioned batteries and indoor conditioned batteries.

Lifetime performance and SOH assessment is conducted based on existing and proposed standards and test methods, described in Section II.. Finally, long-term Li-ion battery capacity degradation is compared to modeled prediction. Multiple samples of the same product at different thermal and depth-of-discharge profiles allow lifetime models to be assessed at multiple realistic use conditions.

II. Test Procedures and Lifetime Models

Outdoor field-testing of commercial products presents challenges relative to lab-scale indoor cycling tests. The largest challenge is the lack of control over the thermal environment because battery capacity is typically reported at 25°C. Also, the battery management systems (BMS) of commercial products can limit the available power and discharge rate (C-rate) and can prevent access to terminal voltages. Other challenges of field lifetime testing relative to indoor accelerated cycling include the inability to isolate specific aging conditions—such as temperature, C-rate, and depth of discharge (DOD)—because of the small sample size. Relevant reported parameters are shown in Table II.

TABLE II. BATTERY PERFORMANCE PARAMETERS

Metric	Description
E_{dis} (Wh)	Total energy on discharge
E_{ch} (Wh)	Total energy on charge
E_N (Wh)	System rated energy
LCOE ($/kWh)	Levelized cost of energy
Q_0 (Ah)	Initial system capacity
SOC, SOH (%)	State of charge, state of health

A. Reference Performance Tests and Real-Time Monitoring

The procedures in [13] describe periodic battery health tests (reference performance tests, or RPT) along with real-time monitoring (RTM) during actual use; however, the methods assume 25°C conditions for RPT discharge, which might only be available seasonally for outdoor systems. In this experiment, C/5 constant-power discharge tests are conducted at prevailing temperature to the minimum state of charge (SOC) allowed by the BMS.

RTM tabulates cumulative energy on charge (E_{ch}) and discharge (E_{dis}). Round-trip efficiency is calculated daily with a correction for SOC difference at the start and end of the period, SOC_{start} and SOC_{end}:

$$\eta_{RTM} = \frac{\sum E_{dis} + E_N(SOC_{start} - SOC_{end})}{\sum E_{ch}} \tag{1}$$

The temperature dependence of battery capacity is important to establish. During RPT battery health tests, the measured capacity Q[Ah] is typically corrected to 25°C by (2) based on empirical coefficients ($Q_{0,ref}, E_{a1}, E_{a2}$) established during initial performance trials. Example temperature dependence of other commercial Li-ion cells Q_0 is shown in Fig. 1 based on reported values in [11]. This dependence is replicated in battery performance and lifetime model capabilities of the National Renewable Energy Laboratory's (NREL's) System Advisor Model (SAM) [14].

$$Q_0 = Q_{0,ref} \exp\left[-\frac{E_{a1}}{k_B}\left(\frac{1}{T} - \frac{1}{T_0}\right) - \left(\frac{E_{a2}}{k_B}\right)^2 \left(\frac{1}{T} - \frac{1}{T_0}\right)^2\right] \tag{2}$$

Fig. 2 shows η_{RTM} plotted against the battery temperature during morning charge, which is within 0.5°C of ambient temperature on average. Compared with the strong predicted temperature dependence of capacity shown in Fig. 1, the round-trip efficiency remains relatively constant with respect to temperature. The average efficiency at 25°C is 0.85, and the efficiency at 0°C is 0.83, suggesting a slight temperature dependence of +0.08%/C (relative).

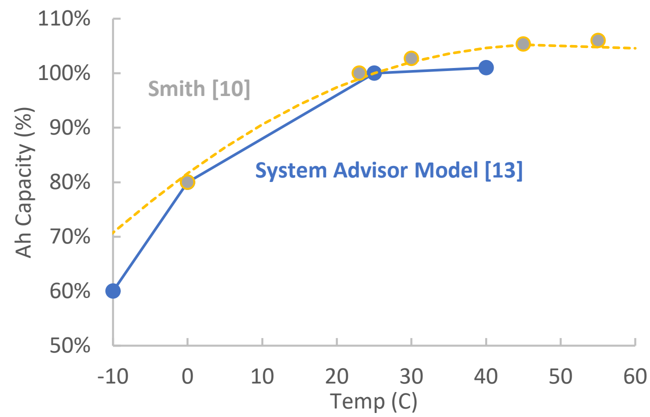

Fig. 1. Modeled battery Ah capacity Q0 shows reduction at low T, per (1). Outdoor RPT tests must be corrected to a common reference T0 to allow comparison over time.

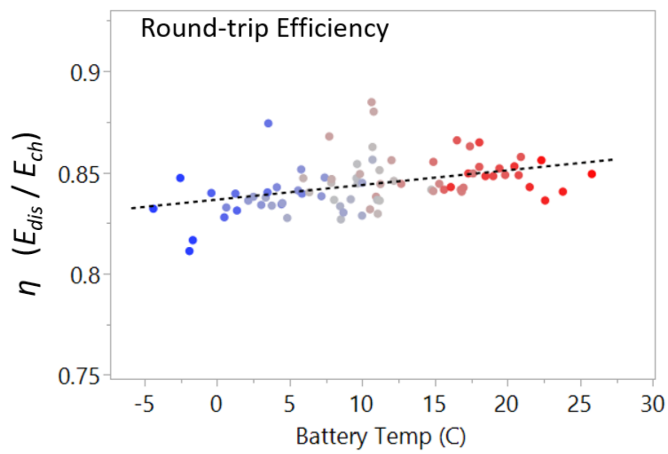

Fig. 2. LG RESU7H round-trip efficiency η_{RTM} = (E_{dis} / E_{ch}) measurements show more uniform performance with battery temperature than indicated by the model in Fig. 1.

B. Li-ion Lifetime Modeling

Two life-limiting mechanisms known for Li-ion batteries are briefly discussed here, and models and predicted results for our field conditions are described. The first loss mechanism is calendar aging, and the second mechanism is cycling loss.

Calendar aging loss has been shown to follow a $t^{1/2}$ dependence as a result of the formation of a solid-electrolyte interphase (SEI) [9], along with an Arrhenius dependence on temperature. A further dependence on SOC has also been identified, showing that the highest calendar fade occurs at high temperature and high SOC. This SOC dependence has variously been identified as being exponential with pack voltage U [10], [11] or linear in voltage [15]. Here, we describe our calendar fade model after [11], where Q_{Li} indicates the capacity loss as a result of the free cyclable Li being lost to SEI growth.

$$Q_{Li} = Q_0 - b_1 t^{1/2} - b_2 N \tag{3}$$

$$b_1 = b_{1,ref} \exp\left[-\frac{E_{a3}}{k_B}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \exp\left[\alpha\left(\frac{U}{T} - \frac{U_0}{T_0}\right)\right] \tag{4}$$

where E_{a3} is the thermally-induced activation energy (0.63 eV), and α is the exponential voltage-dependent factor (930 K/V).

The second life-limiting effect captured here is capacity loss through cycling the battery. As shown in [16], two mechanisms dominate: a loss of negative anode active sites because of Li plating at low-temperature charging and an increase in SEI formation at high-temperature cycles. The first effect is captured in a cycling fade model after [11], where Q_{neg} indicates the loss in available negative electrode active sites from low-temperature cycling stress and fatigue. This is proportional to the square root of cycle number *N*.

$$Q_{neg} = [c_0^2 - 2c_2 c_0 N]^{\frac{1}{2}} \quad (5)$$

Here, c_2 is dependent on *T* and DOD:

$$c_2 = c_{2,ref} \exp\left[\frac{-E_{a4}}{k_B}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] DOD^{\beta} \quad (6)$$

where E_{a4} is the activation energy -0.5eV, and β = 4.54.

The second half of cycling loss—increased SEI formation at high temperature—is stated by the second term in (3), which is proportional to cycle number *N*. The parameter b_2 also follows an Arrhenius dependence, with activation energy 0.44 eV.

The overall life model is developed by a combination of (3) and (5), assuming that the two processes proceed somewhat independently. Therefore, the system capacity evolution with time *Q*(*t*) is the lesser of these two equations. This process is captured for simplified cases in NREL's SAM [14] and more completely in the Battery Lifetime Analysis and Simulation Tool (BLAST) [17]. The evolution of series resistance is also an important aspect of battery SOH, and it is captured in the BLAST model, but is not discussed here.

III. Equipment Under Test

Fig 3. Field-deployed LG RESU7H battery along with 3.3-kW hybrid inverter and DC monitoring. (Photo by Chris Deline)

Field-aging studies of DC-coupled BESS systems were initiated in 2018 with the purchase of three Li-ion and two vanadium redox flow batteries. The 7-kWh Li-ion batteries are each charged by a 3.3-kW PV array and discharged through a 3.3-kW hybrid inverter (Fig 3). The 30-kWh flow batteries are each charged by a 7-kW PV array and discharged through a 10-kW hybrid inverter. Additional system details and operating conditions are provided in Table I. The batteries are configured to discharge nightly to their lower SOC set point and recharge during the following day, to the extent that the PV is able to charge based on the weather.

Monthly RPT tests at ambient conditions are conducted to assess the remaining capacity and evaluate the battery SOH. Round-trip efficiency parameters are also tabulated daily from E_{ch} and E_{dis} (1).

Validation of capacity fade models are done in part by isolating parameters affecting Q_{Li} and Q_{neg} in (3) and (5). These include temperature, DOD, and C-rates. Testing conditions and load-cycling profiles are selected to determine the effects of these stressors on the overall capacity loss.

Variations in temperature are conducted by installing the BESS in an indoor or outdoor location. The indoor BESS are installed in a temperature-controlled container. The outdoor BESS are installed adjacent to the PV powering it, subject to ambient conditions in Golden, CO.

The DOD and C-rate are controlled through the inverter interface. The DOD is controlled by changing the lower SOC set point, and the C-rate is controlled by varying the time window over which the discharge is configured to occur. These settings are shown in Table I.

IV. Results

A. Li-ion Initial Efficiency and Thermal Response

Initial RPT discharges are conducted on the RESU7H battery to establish Q_0 initial capacity. Fig. 4 represents an initial discharge from 100% SOC to 15% SOC, conducted at 11.3°C and C/4 discharge rate.

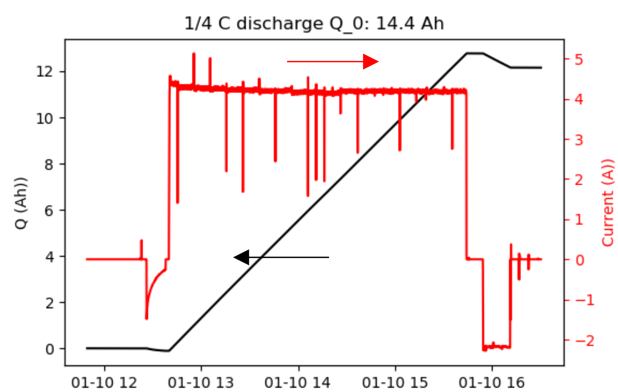

Fig 4. Initial Q_0 discharge test for LG RESU7H at C/4 rate.

A typical plot of ambient temperature vs. battery internal temperature (Fig. 5) shows that during morning charging, the battery largely follows outdoor ambient temperature, with a slight time delay because of the thermal mass of the battery. Morning charging occurs at a rate dictated by available solar resource, up to a maximum of 1.75 kW (C/4). A typical energy value to reach 100% SOC is 5.3 kWh at 25°C.

Upon discharge in the evening (triggered daily at 4 p.m.), the battery temperature increases 4°C by internal self-heating. Efficiency remains constant, with a typical 4.5-kWh E_{dis}.

Battery bus voltage varies between 400 V–420 V during charge and discharge. Because of the BMS of the RESU7H, which includes a boost DC-DC converter, it is difficult to draw conclusions about internal battery SOC based on bus voltage, and externally measured amp-hour capacity Q is not necessarily conserved on charge and discharge.

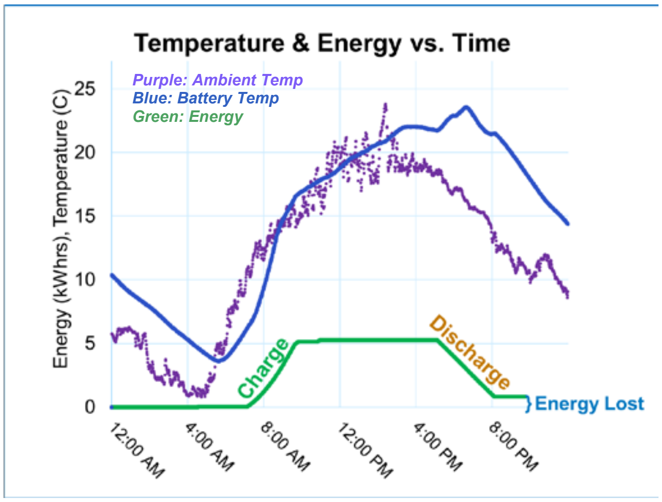

Fig 5. Ambient temperature vs. internal battery temperature during charge (< 11 a.m.) and discharge (> 4 p.m.)

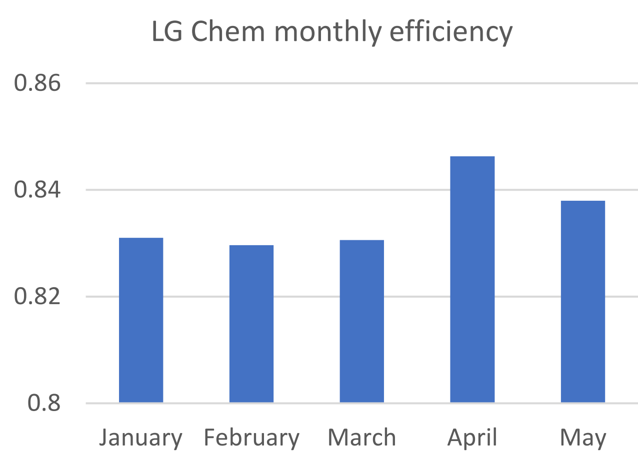

Fig. 6. Monthly round-trip efficiency for LG Chem RESU7H

The efficiency of the outdoor RESU7H is tabulated monthly and shown in Fig. 6. Because of the relatively low temperatures during morning charging in the winter and early spring, round-trip efficiency remains less than 0.85 on average. Note that May represents a partial month with low temperatures, leading to lower reported η_{RTM} than in April.

B. Li-ion Lifetime Model and Field Results

As described previously, the aging of Li-ion batteries depends on ambient conditions, cycling use, and calendar age. To estimate approximate operating conditions and cycle life of the batteries under test, a SAM model is run using the typical Golden, CO, climate and PV system parameters. Because of the nightly full discharge to 15% SOC, the average battery SOC during the 10-year study is 31%, and daily charge depth averages 62%. Ambient temperatures also average 7°C, with a 14°C daily high average.

Using these ambient conditions, lifetime estimates based on these cited parameters are plotted in Fig. 7. Published lab cycling data on the LG RESU7H from the Lithium Ion Battery Test Centre in Australia [18] are also shown in Fig 7. Predicted lifetimes of Smith [11] are based on Kokam NMC cells. Schmalstieg [15] is based on Sanyo NMC cylindrical cells, and Ecker [10] uses NMC pouch cells.

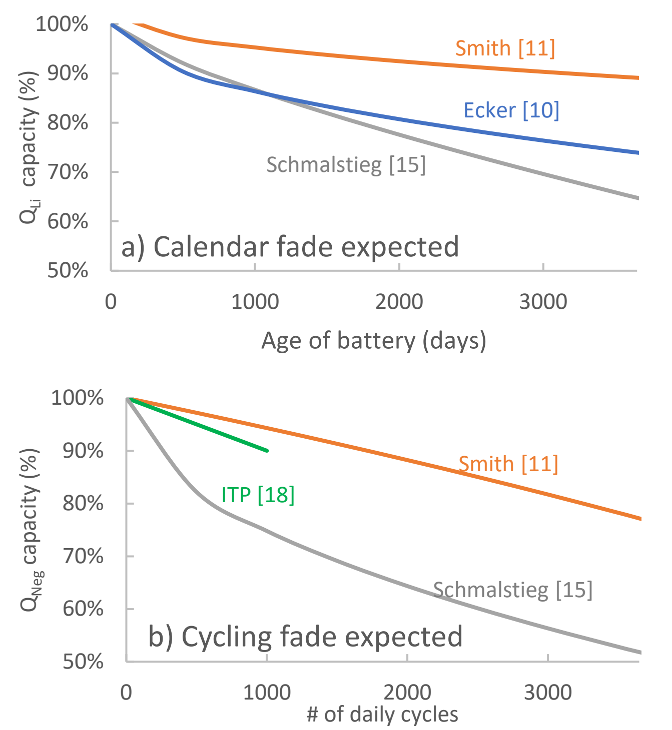

Fig 7. Li-ion lifetime simulations based on expected ambient conditions during the first 10 years of deployment and actual LG RESU cycle data from [18].

Four months of cycling data are collected from the outdoor-deployed RESU7H. Daily discharges from which the battery reached full SOC are shown in Fig. 8.

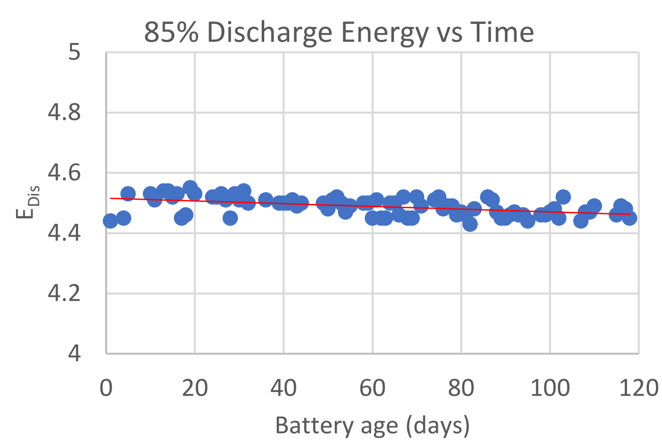

Fig 8. Measured discharge capacity of the outdoor RESU7H during 120 daily discharges. Overall reduction in E_{dis} capacity is -1.2%.

The reduction to date is modest: after only 120 daily cycles, the lost battery Wh capacity is -1.2%. This is on pace for a -3.7% annual performance loss, which is comparable to the rate of degradation found by indoor cycling of this product [18].

Cycles on the indoor comparison batteries are only now beginning, along with the Avalon vanadium redox flow battery cycles. The performance of these units will be detailed in future publications.

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