Direct Comparison of State-of-Charge and State-of-Energy Metrics for Li-Ion Battery Energy Storage

***Abstract*—This paper presents a direct experimental evaluation of differences between state-of-charge (SOC) and state-of-energy (SOE) metrics for lithium-ion storage batteries. This paper first investigates the SOC-SOE metric differences for single constant-current-constant-voltage (CCCV) cycles under room temperature (25°C) conditions to understand the significance of incorporating voltage into the SOE metric. Experimental results show that the SOC-SOE difference values are a function of C-Rate, where larger C-Rates result in larger metric differences. This investigation has also shown that lower ambient temperatures increase the SOC-SOE difference values, mirroring the effects of temperature on battery voltage. Finally, tests investigating the effects of battery aging on these metrics indicate that the SOC-SOE difference values increase as the batteries age, suggesting that the SOC-SOE difference variable holds potential for use in state-of-health estimation.**

Keywords—State-of-charge, state-of-energy, Lithium-Ion battery, operating temperature, battery aging, degradation

I. INTRODUCTION

All applications ranging from consumer electronics to electric vehicles that operate using lithium-ion battery energy storage need a means to track and report the current state of the battery to maximize the application performance. State-of-Charge (SOC) is the dominant metric used in EVs as an equivalent fuel gauge for range prediction, as well as for insuring safe operation of the batteries [1], [2]. In its simplest form, SOC is the integral of the battery current normalized by the battery system's rated charge capacity that represents the battery system's remaining capacity as a percentage value. SOC has been a popular research topic for many years as the demand for longer battery system operation and higher reliability has become increasingly important. In its simplest form, SOC can be tracked by calculating the current integral in real-time, but alternative methods for SOC estimation have been proposed and evaluated as well [3]–[5].

The most common method for SOC estimation is Coulomb Counting (or Ah Counting) based on accurate current integration. However, basic coulomb counting lacks adaptability for battery aging (e.g., State-of-Health), ambient temperature, or the discharging rate efficiency [3]. Due to these issues, academia and industry have focused significant efforts to develop enhanced SOC estimation methods that take one or more of these factors into account. Equivalent circuit modeling for SOC estimation has been heavily investigated as a means of error reduction by taking temperature effects into account [4], [6], [7]. Until recently, research has focused on methods to reduce the SOC metric error rather than finding new metrics/methods that fundamentally take these factors into account. State-of-Energy (SOE) was introduced as a metric that could potentially rival SOC as a means to estimate battery states in applications [8]. SOE is a metric that bears some similarities to SOC, but instead of integrating the current alone, the SOE metric uses a power integral that incorporates the battery voltage into the integrand. Since temperature, aging, and discharge rate are reflected in the battery voltage behavior, incorporating the voltage into the SOE metric suggests that it could be employed to better monitor and manage the battery system's energy than SOC [9], [10].

Although SOE has not been investigated as extensively as SOC, research has been conducted during the past few years to better understand how this metric behaves. Established methods for SOC tracking were adapted for use with the new SOE metric, such as online estimation methods with equivalent circuit modeling, as well as understanding how the SOE metric behaves with varying discharge rates [11], [12]. While research has been conducted to understand how the online estimation of SOE can be performed, little effort has been devoted to explaining where the differences between the SOC and SOE metrics lie. The purpose of this research is to conduct controlled experiments that directly compare the SOC and SOE metrics for lithium-ion batteries in order to improve our understanding of how these metrics perform. Very importantly, effort has been devoted to understanding how the SOE metric is influenced by combinations of factors including discharge rate, ambient temperature, and battery aging. Revealing how SOC and SOE differ is crucial to understanding whether SOE is viable and appealing as a replacement method for SOC.

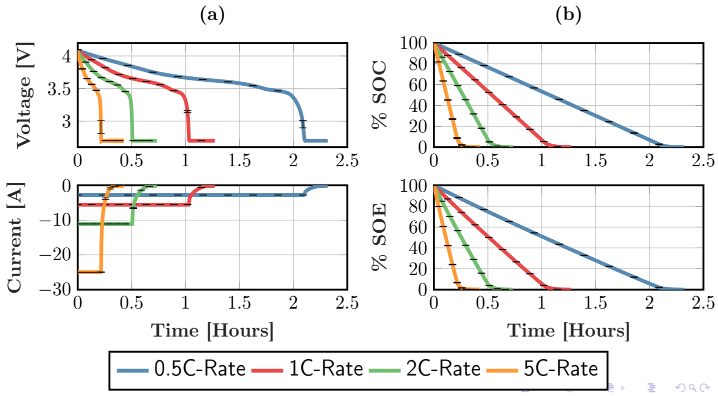

Fig. 1. Experimental results for the room temperature (25°) study, where: (a) shows the voltage and current profiles vs. time, and (b) shows the SOC and SOE metric results for these tests. Average values for 5 cells are plotted, with error bands included as black horizontal lines.

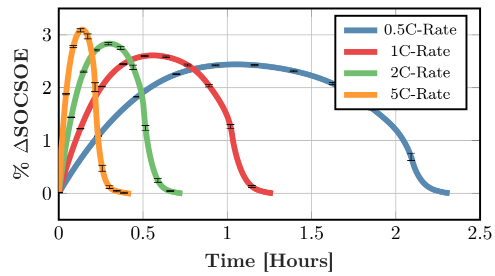

Fig. 2. Experimental values for the ΔSOCSOE difference metric derived from the room temperature test results in Fig. 1. Error bars are included as black horizontal lines.

Section II defines the methods for calculating both SOC and SOE that are used during the experiments presented in Section III. In Section III, experimental results are presented for a Constant-Current-Constant-Voltage (CCCV) discharge test protocol carried out at room temperature (25°C) to understand how the metric results differ over a complete discharge range extending up to full (100%) Depth-of-Discharge (DOD). Results are next presented for experiments that were conducted to understand how the SOC-SOE metric differences are influenced by important factors such as ambient temperature, discharge current-rate (C-Rate), and battery aging. Section IV summarizes the key results and conclusions derived from this investigation.

II. Derivation of SOC and SOE Metrics

The SOC metric is calculated using (1) by integrating the battery terminal current and normalizing by the rated capacity C_n to form a dimensionless percentage value. The SOE metric is evaluated in a similar fashion as the SOC using (2), where SOE integrates the battery power by forming the product of the instantaneous battery current and voltage, and then converting this integral into a percentage by normalizing using the rated battery energy E_n.

$$SOC\% = \frac{\int_{t_0}^{t_1} \eta_e I(t)dt}{C_n} * 100\% \qquad (1)$$

$$SOE\% = \frac{\int_{t_0}^{t_1} \eta_e V(t)I(t)dt}{E_n} * 100\% \qquad (2)$$

In both (1) and (2), η_e in the integrand represents the battery's coulombic efficiency, and it has been neglected in this investigation (i.e., $\eta_e = 1$) in order to focus attention more directly on the difference between the SOC and SOE metrics caused by incorporating the battery voltage into the SOE integration. Since the battery voltage reacts to the discharge rate, ambient temperature, this project was designed to investigate whether the SOE metric is better adapted to capturing the impact of these factors than the SOC which is insensitive to these factors without adopting a more complicated version of the SOC metric.

III. Experimental Evaluation of Metric Differences

All experiments in this project were performed using the same type of nominally-rated 5.8Ah prismatic lithium-ion cell. A Digatron battery testing system was used to charge/discharge the batteries that were placed in thermal chambers to control their ambient temperatures during the experiments [13].

A. Single Discharge Event Comparison

The first experiment conducted was a constant-current-constant-voltage (CCCV) discharge event at room temperature. This experiment used 5 cells, with 3 CCCV cycles performed for each cell, yielding average and standard deviation values that provide the basis for test results presented in this digest. The error bands are included in Fig. 1 and Fig. 2, indicating that the standard deviation is small. The error bands are comparably narrow for all of the remaining tests conducted during this study, so they are not included in the remaining figures in this digest.

Fig. 1 shows the results for the room temperature CCCV test protocol, where (a) shows the voltage and current profiles for each of the four C-Rate values tested, and (b) shows the SOC and SOE metric results for the experiment when utilizing (1) and (2), respectively. Since the difference between the SOC and SOE values are difficult to determine from these waveforms, a new variable ΔSOCSOE was defined (3) to form the difference between the SOC and SOE values at each time instant. The resulting values of ΔSOCSOE for each of the four C-Rates are plotted in Fig. 2 to highlight the SOC-SOE metric differences during the CCCV tests at room temperature.

$$\Delta SOCSOE[k] = SOC[k] - SOE[k] \tag{3}$$

Examining the results in Fig. 2, three significant observations can be made. First, it is interesting to note that the peak value of the SOC-SOE difference variable always occurs at approximately the midway point of each CCCV test. Second, the peak value of SOC-SOE differences increases with higher C-Rates. Third, the metric differences are always positive, meaning that the SOE value is always less than or equal to the SOC throughout each test. This third point implies that if any application sets the same lower limit on the SOC and SOE values (i.e., a maximum limit on the depth-of-discharge (DOD)), the SOE will reach the lower limit before the SOC. Since the SOE metric takes the battery voltage into account while SOC does not, this raises questions about whether the SOC-SOE difference variable might provide useful information about battery aging. This topic is addressed later in this digest in Section C.

B. Discharge Event Metric Differences at Various Ambient Temperatures

A series of experiments was carried out to evaluate the impact of the ambient temperature on the SOC-SOE metric differences. This experiment used 5 cells, with 3 CCCV cycles performed on each cell at the three ambient temperatures that were tested (10°C, 25°C, 45°C). The average values for each cell are plotted in Fig. 3. As noted earlier, no error bands are included because they are so narrow.

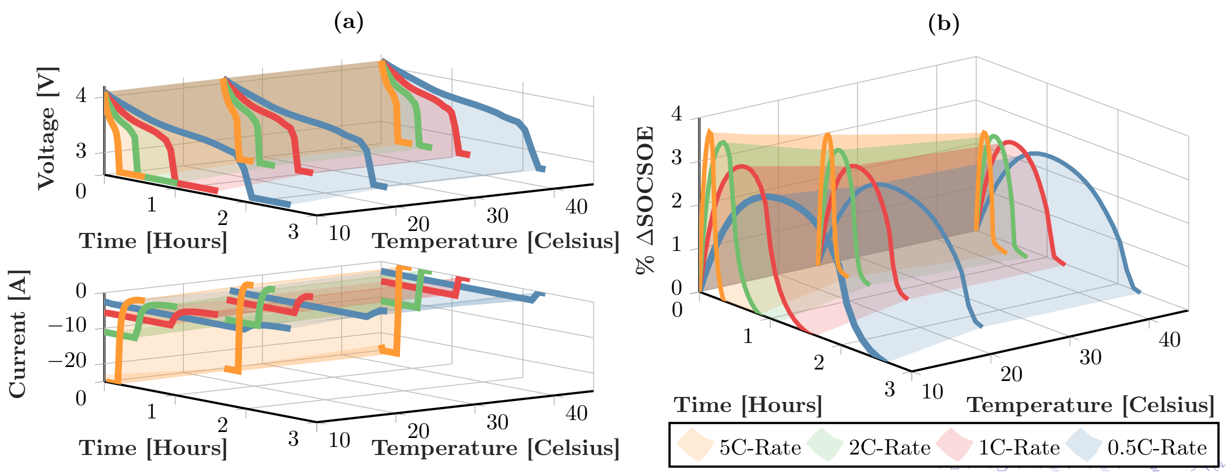

Fig. 3 Experimental results for the ambient temperature study, where (a) shows the voltage and current profiles vs. time and temperature, and (b) shows the ΔSOCSOE discharge profile as a function of time and temperature.

Fig. 3 shows the experimental results from these tests, where Fig. 3(a) shows the voltage and current profiles for all three temperatures. Fig. 3(b) shows the SOC-SOE difference variable ΔSOCSOE for the three ambient temperatures. Consistent with the 25°C results, the SOC-SOE differences increase as the C-Rate increases for both the higher and lower temperatures as well. However, these tests also show that the amplitude of ΔSOCSOE for each of the C-Rates increases as the ambient temperature is reduced. Closer examination of the SOC and SOE results from these tests reveals that changes in the SOE are predominantly responsible for these ΔSOCSOE difference trends because of the well-known sensitivity of the battery voltage to temperature which directly affects the difference between the calculated SOE and SOC values in (1) and (2). In fact, the increase in the ΔSOCSOE amplitude as the temperature decreases mirrors the increasing drop in the battery terminal voltage at a given C-Rate as the temperature is reduced.

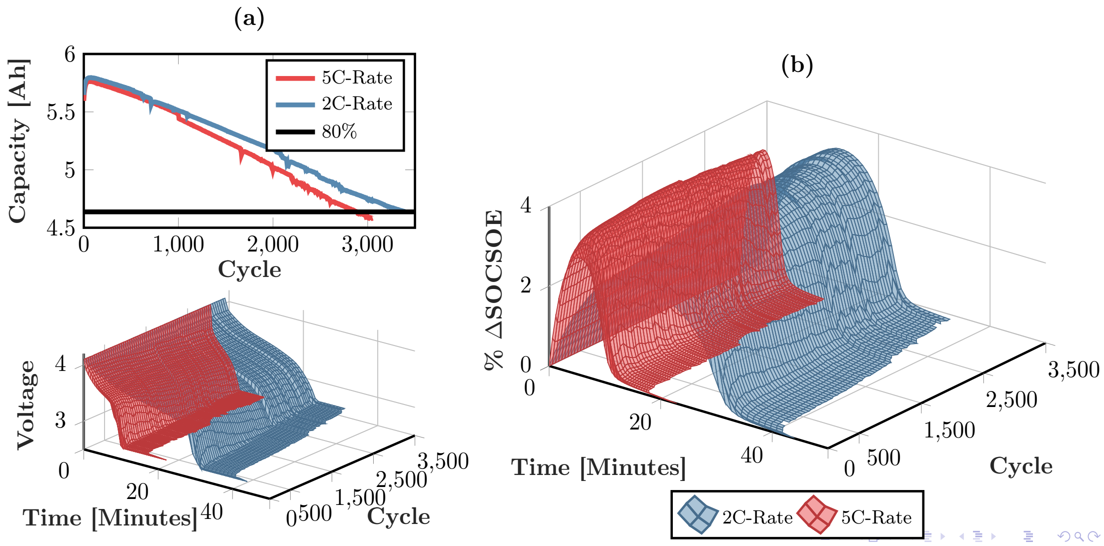

Fig. 4. Experimental results for the battery aging study carried out at 25°C where: (a) shows the battery capacity as a function of cycle for each of the two studied C-Rates in the upper plot, and the voltage profile as a function of time and cycle number in the lower plot, and (b) shows the ΔSOCSOE difference discharge profile as a function of time and cycle number for the two C-Rates.

C. Impact of Battery Aging on SOC-SOE Difference

Extending the analysis beyond temperature and C-Rate dependence, the next step in the investigation was to study how the SOC-SOE differences behave as a battery ages. For this experiment, 3 fresh batteries of the same type used in the preceding tests were subjected to controlled aging tests at two C-Rates (2C, and 5C), conducted at room temperature (25°C). The aging tests consist of continuous cycling through the CCCV protocol. The capacity was tracked via the Digatron testing system, which uses a current integral evaluating at every sampling time within the system. Extraction of the individual capacity discharged in each cycle provided the capacity tracking used to monitor the battery aging.

Fig. 4(a) shows both the measured battery capacity vs. test cycle number, and the measured voltage profile vs. time as a function of the cycle number for both C-Rates. The measured capacity values provide a convenient means of tracking the battery aging process and detecting when they each reached their failure thresholds, defined to be 80% of their initial measured Amp-hour capacities (= 0.8*5.8 = 4.6 Ah). The voltage profile as a function of cycle can be used to observe the transition times between constant-current and constant-voltage operation for each CCCV cycle. Fig. 4(b) plots ΔSOCSOE variable as a function of cycle for both C-Rates. As observed previously, the peak value of this difference variable increases with the C-Rate. However, this test also shows that that the peak value of ΔSOCSOE increases vs. the cycle number as the battery is aged for both C-Rates. It is important to note that the peak value of ΔSOCSOE changes more significantly during the first 100 cycles than during the remainder of the experiment. This can be attributed to the initial formation of the battery which is a well-known phenomenon for these batteries [14].

Understanding how the SOC-SOE metric difference behaves as the battery ages is critical to determining whether SOE shows any potential as a tracking method for Li-ion battery aging in battery system applications. Fig 4(b) exhibits a gradual and near-linear increase in the peak ΔSOCSOE value for a given C-Rate and temperature. This suggests that, rather than depending on the SOC metric alone, a battery management system (BMS) could benefit from tracking both SOC and SOE and the difference between them. By tracking the ΔSOCSOE, the peak value of this difference variable could be calculated during discharge events to aid in determining the state-of-health (SOH) of the battery cells. An attractive feature of this proposed technique is that all of the sensors needed to calculate the SOE and ΔSOCSOE (i.e., individual battery cell voltage, battery current, battery temperature) are already available in commercial Li-ion battery systems.

IV. CONCLUSIONS

The results of this study provide clear evidence that the SOC and SOE metrics for lithium-ion batteries behave differently during simple charge/discharge tests because of the presence of the battery voltage in the integrand of the SOE metric. Attention has been focused specifically on the differences between the SOC and SOE metrics by forming the ΔSOCSOE difference variable, revealing features and trends that have not been previously discussed in the literature. Summarizing, the experimental tests have shown that the peak value of the ΔSOCSOE difference variable during CCCV discharge increases as the C-Rate is increased or the battery ambient temperature is reduced.

The results of these tests raise the possibility that monitoring the SOE during battery operation in depletion-mode applications and using a lower-limit SOE threshold value for shutdown might be a more accurate way of evaluating the battery's true discharge state since, unlike SOC, the SOE variable incorporates the effects of voltage changes directly into its instantaneous value. In addition, aging tests revealed that the peak ΔSOCSOE difference for a given C-Rate and ambient temperature increases almost linearly as the battery ages, suggesting possibilities for its use in SOH monitors.

More detailed test results and discussion about the differences between SOC and SOE metrics will be included in the final paper.

REFERENCES

[1] S. Piller, M. Perrin, and A. Jossen, "Methods for state-of-charge determination and their applications," *J. Power Sources*, vol. 96, no. 1, pp. 113–120, 2001.

[2] J. Garche, A. Jossen, and H. Dijring, "The influence of different operating conditions, especially over-discharge, on the lifetime and performance of lead/acid batteries for photovoltaic systems," 1997.

[3] K. S. Ng, C. S. Moo, Y. P. Chen, and Y. C. Hsieh, "Enhanced coulomb counting method for estimating state-of-charge and state-of-health of lithium-ion batteries," *Appl. Energy*, vol. 86, no. 9, pp. 1506–1511, 2009.

[4] Xidong Tang, Xiaofeng Mao, Jian Lin, and B. Koch, "Li-ion battery parameter estimation for state of charge," *Proc. 2011 Am. Control Conf.*, pp. 941–946, 2011.

[5] S. Piller, M. Perrin, and A. Jossen, "Methods for state-of-charge determination and their applications."

[6] S. J. Lee, J. H. Kim, J. M. Lee, and B. H. Cho, "The State and Parameter Estimation of an Li-Ion Battery Using a New OCV-SOC Concept," *2007 IEEE Power Electron. Spec. Conf.*, no. July, pp. 2799–2803, 2007.

[7] M. Verbrugge and E. Tate, "Adaptive state of charge algorithm for nickel metal hydride batteries including hysteresis phenomena," *J. Power Sources*, vol. 126, pp. 236–249, 2004.

[8] B. Y. Mamadou, K., Lemaire, E., Delaille, A., "The State-of-Energy- A New Criterion for the Energetic Performances Evaluation of Electrochemical Storage Devices," vol. 25, no. 35, pp. 105–112, 2010.

[9] W. Waag, C. Fleischer, and D. U. Sauer, "Critical review of the methods for monitoring of lithium-ion batteries in electric and hybrid vehicles," *J. Power Sources*, vol. 258, pp. 321–339, 2014.

[10] X. Liu, J. Wu, C. Zhang, and Z. Chen, "A method for state of energy estimation of lithium-ion batteries at dynamic currents and temperatures," *J. Power Sources*, vol. 270, pp. 151–157, 2014.

[11] G. Dong, Z. Chen, J. Wei, C. Zhang, and P. Wang, "An online model-based method for state of energy estimation of lithium-ion batteries using dual filters," *J. Power Sources*, vol. 301, pp. 277–286, 2016.

[12] K. Li, K. J. Tseng, and L. Moraleja, "Study of the Influencing Factors on the Discharging Performance of Lithium-ion Batteries and Its Index of State of Energy," pp. 0–6, 2016.

[13] JCI, "Johnson Controls - Power Solutions," 2016. [Online]. Available: https://www.johnsoncontrols.com/suppliers/batteries.

[14] J. H. Lee, H. M. Lee, and S. Ahn, "Battery dimensional changes occurring during charge/discharge cycles - Thin rectangular lithium ion and polymer cells," *J. Power Sources*, vol. 119–121, pp. 833–837, 2003.