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Accelerated energy capacity measurement of lithium-ion cells to support future circular economy strategies for electric vehicles

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ABSTRACT

Within the academic and industrial communities there has been an increasing desire to better understand the sustainability of producing vehicles that contain embedded electrochemical energy storage. Underpinning a number of studies that evaluate different circular economy strategies for the electric vehicle (EV) or Hybrid electric vehicle (HEV) battery system are implicit assumptions about the retained capacity or State of Health (SOH) of the battery. International standards and best-practice guides exist that address the performance evaluation of both EV and HEV battery systems. However, a common theme is that the test duration can be excessive and last for a number of hours. The aim of this research is to assess whether energy capacity measurements of Li-ion cells can be accelerated; reducing the test duration to a value that may facilitate further EOL options. Experimental results are presented that highlight it is possible to significantly reduce the duration of the battery characterization test by 70–90% while still retaining levels of measurement accuracy for retained energy capacity in the order of 1% for cell temperatures equal to 25 °C. Even at elevated temperatures of 40 °C, the peak measurement error was found to be only 3%. Based on these experimental results, a simple cost-function is formulated to highlight the flexibility of the proposed test framework. This approach would allow different organizations to prioritize the relative importance of test accuracy verses experimental test time when grading used Li-ion cells for different end-of-life (EOL) applications.

1. Introduction

There has been considerable research published into the different designs and technology options that underpin the energy storage system (ESS) employed within new electric vehicle (EV) or hybrid electric vehicle (HEV) concepts. This includes the use of different battery chemistries [1], the design of the energy management control software [2–4] and the mechanical integration of the battery system within the vehicle [5]. The primary motivation is often to overcome the systems engineering challenge and to design an ESS with an energy density and power density that will enable the design of new vehicles with a driving range and dynamic performance commensurate with consumer expectations. In addition to improving *on-vehicle* metrics of energy density, power density and component cost, there has been an increasing desire to better understand the sustainability of producing vehicles that contain embedded electrochemical energy storage. Much of this research has been guided by circular economy principles. The term circular economy has come to embody any framework that advocates an alternative to the traditional linear economic model (make, use, dispose); retaining key resources within the supply chain for longer, extracting the maximum value from them whilst in use before embarking on a process of regenerating products and materials at the end of their service life [6].

Underpinning a number of studies that critically evaluate different circular economy strategies for the vehicle's ESS are implicit assumptions about the State of Health (SOH) of the battery [7–9]. The metric SOH is often used to quantify the residual energy capacity of the cell at a time (t=n), relative to when the battery was new (t=0):

$$SOH = \frac{Q_{t=n}}{Q_{t=0}} \quad (1)$$

End-of-life (EOL) for the vehicle's ESS has been defined as the battery having a SOH of 80% [7,10–13]. However, a number of studies highlight the apparent arbitrary nature of this threshold value. It is

Abbreviations: ADC, Analogue-to-digital converter; BEV, Battery Electric Vehicles; BMS, Battery management software; CC, Constant current; CV, Constant voltage; DOE, Department of Energy; EERE, Energy Efficiency and Renewable Energy; EOL, End-of-life; ESS, Energy storage system; EV, Electric Vehicle; HEV, Hybrid electric vehicle; HVM, High Value Manufacturing; ICE, Internal combustion engine; INL, Idaho National Laboratory; LCA, Life-Cycle Assessment; NEDC, New European Drive Cycle; PHEV, Plug-in Hybrid Electric Vehicles; SOC, State of charge; SOH, State of Health; USABC, US Advanced Battery Consortium

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often argued that even at 80% SOH, there is still inherent value embedded within the ESS [13–15].

Research by [2,16] argues that a measure of battery SOH should be calculated by the battery management software (BMS) and made available to all stakeholders within the supply chain via standard diagnostic interfaces and vehicle communication networks. To maximize the efficiency of the EOL strategy and to facilitate the repair, remanufacture or reuse of the battery system, SOH measurements should be made available for each battery module that comprises the battery pack (Section 2.2 discusses, in greater detail, the architecture of a typical vehicle battery system and the methods employed to aggregate cells into modules and finally into complete packs). However, from a review of commercially available EVs and HEVs, it is clear that this is not always the case, for example: the BMS within the Tesla vehicle does not provide information on battery SOH that can be viewed by a third-party, independent from the manufacturer. Assessing the battery installation for degradation, requires the battery pack to be removed from the vehicle, physically opened (that in turn damages the mechanical structure of the pack) and individual modules tested for retained capacity and impedance to quantify their SOH. This challenge is compounded, since it is likely that vehicle batteries will be presented to the supply-chain with unknown provenience and with varying levels of functionality [17]. A challenge therefore exists for those stakeholders wishing to sort or grade used vehicle battery systems to ascertain the most appropriate circular economy strategy for the battery that may comprise of: battery repair, reuse, remanufacturing or materials recycling in order to maximize the capture of the battery's inherent value.

International standards and best-practice guides exist that address the performance evaluation requirements for the both EV and HEV battery systems. Each standard addresses different domain requirements for performance, robustness and safety a nd how testing should be undertaken at either a cell (i.e. IEC-62660 and ISO-12405) or system level (i.e. United States Council for Automotive Research (USABC) Electric Vehicle Battery Test Procedures Manual). Within the context of this research and in line with the need to better understand residual energy capacity to assess battery SOH, particular consideration is given to the recommended procedures for cell-level capacity measurement. Irrespective of the test standard followed, a common theme throughout is that the test duration, taking into account the time required for the cell to equilibrate after a change in ambient temperature or state of charge (SOC) can be excessive and last for a number of hours. For this reason, the authors argue that these test strategies are potentially prohibitive for a number of vehicle manufacturers and specialist energy storage suppliers wishing to sort or grade used vehicle battery systems to ascertain the most appropriate circular economy strategy for the battery.

The aim of this research is to assess whether energy capacity measurements of Li-ion cells can be accelerated, reducing the test duration to a value that may facilitate further EOL options for used EV and HEV battery systems. In addition, the research aims to quantify the trade-off between test accuracy and test time, potentially allowing stakeholders to optimise the evaluation strategy they employ within the context of their respective commercial sectors.

This paper is structured as follows; Section 2 provides an overview of the automotive market and ESS technology solutions currently employed. Section 3 discusses, in greater detail, different EOL strategies for automotive battery systems. Section 4 introduces the different international standards and best-practice guides that are often employed as the basis for battery characterization. Section 5 discusses the experimental method derived to compress the time required to assess the retained energy capacity within the cell. Results, Discussions and Conclusions from this research are presented in Sections 6, 7 and 8 respectively.

2. Market and technology overview

2.1. Market overview for electrified vehicles

A recent 2015 report by KPMG [18] highlights the potential for electrified vehicles to be between 11–15% of new vehicle sales within the EU and China by 2025. Within the US, the market may comprise 16–20% of vehicles over the next 10 years. These predictions are comparable to those cited in [15]. The article collates a number of studies and concludes that, by 2025, there will be in excess of 11 million EV sales worldwide, with approximately 6 million in North America (20% of new vehicle sales). While a number of sources predict rapid sales growth, there are variations in the predicted technology-mix that will underpin this. In particular, the relative sales of HEVs that typically employ a smaller battery system (e.g. Toyota Prius Plug-in Hybrid Electric Vehicles (PHEV), with a 4.4 kW h battery), compared to an EV (e.g. the Nissan Leaf or the BMW i3), which require larger batteries in the order of 24 kWh and 22 kWh respectively. Research presented in [12] predicts that in 2035 the number of available EOL batteries will range from 1.4 million in their pessimistic forecast to 6.8 million in the optimistic forecast with a middle forecast of 3.8 million. Their analysis concludes that this volume is sufficient to justify the capital investment required to enable remanufacturing, repurposing and recycling. Further, their study highlights that the number of available EOL batteries will be between 55% and 60% of the number of batteries needed for new EV and PHEV production.

2.2. Vehicle energy storage systems

A consensus does not exist as to the optimal design of battery cell, in terms of both chemistry and form-factor, for use within automotive applications. There is significant research characterizing the different chemistries, including: Lithium Cobalt Oxide ($LiCoO_2$), Lithium Iron Phosphate ($LiFeP0_4$), Lithium Nickel Cobalt Manganese (NCM – $LiNi_xCo_yMn_xO_Z$) and Lithium Titanate Oxide (LTO – $LI_4Ti_5O_{12}$). The integration challenge associated with designing a complete ESS using either pouch cells or cylindrical 18650 cells is reported within [2,3,19]. In [2] and [19] the authors highlight how cell-to-cell variations and non-uniformity within the cell further complicates ESS integration. Whereas within [3] the authors discuss the instrumentation and on-line monitoring requirements that underpin the battery control software.

It is beyond the scope of this paper to discuss, in detail, the engineering challenges associated with the ESS; further information can be found within [3,20]. To illustrate the complexity within a real-world system, Table 1 presents an overview of the contents of the battery pack within the commercially available Nissan Leaf EV. The Nissan Leaf has a reported range of 109 miles over the New European Drive Cycle (NEDC). The complete battery assembly weighs 293 kg and contains 48 battery modules, each containing 4 Li-ion pouch cells. An active cooling system is not included within the battery, but it does contain an electrical heating element to warm the Li-ion cells. The 48 modules within the battery are grouped together into 3 primary sub-assembles called module stacks, each containing a number of electrical interfaces and mechanical fasteners. The module stacks are accessible once the pack lid has been removed, potentially making it easier to identify and replace faulty components during a repair or remanufacturing activity. The battery pack is held together and attached to the vehicle chassis using 20 mechanical bolts. Within the battery, at the module stack and module levels, a variety of different joining methods are employed, including mechanical screws and bolts, totaling 376 fasteners. It is noteworthy that adhesives or mechanical welds are not employed within the assembly which, as discussed within [10,21,22], can significantly inhibit a number of EOL options for the ESS. The challenges associated with module disassembly due to battery tab welding are explored within [10], whereas the authors within [22]