

Testing of Commercial Electric Vehicle Battery Modules for Circular Economy Applications

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ABSTRACT

Increasingly international academic and industrial communities desire to better understand, implement and improve the sustainability of vehicles that contain embedded electrochemical energy storage. Underpinning a number of studies that evaluate different circular economy strategies for the electric vehicle (EV) 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 in performance testing 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 and internal resistance measurements of Li-ion based modules can be optimized, reducing the test duration to a value that may facilitate further End-of-Life (EoL) options. Experimental results for a Porsche Panamera Hybrid module and a Tesla Model S P85 module that highlight a reduction of the duration of a commercial battery module characterization test by circa 70%. This reduction is accompanied by levels of measurement accuracy for retained energy capacity in the order of 1% for module test temperatures equal to 25°C. Improvement of 85% is achieved for resistance testing while still retaining levels of measurement accuracy in the order of 2% for module temperatures equal to 25°C. Based on these experimental results, a quick characterization test sequence is proposed and within a robust system test framework would allow different organizations to prioritize the relative importance of test accuracy versus experimental test time when grading used Li-ion modules.

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INTRODUCTION

Circular economy activities are becoming increasingly important to ensure business sustainability [1, 2, 3]. The automotive industry has been highlighted as one of the sectors that could financially benefit whilst reducing environmental impact by moving towards a more circular economy [4,5]. The uptake of various types of Electric Vehicles (xEVs) is predicted to be up to 15% of new cars sold in 2025 in the EU market, resulting in 20 million EVs which will result in a dramatic increase in End-of-Life (EoL) traction batteries in the future [6]. Furthermore, legislation such as the European Batteries directive puts a greater financial responsibility on the battery producer [7]. Thus the cited financial, social and environmental benefits in conjunction with the legislative requirements are a major driving force to develop circular activities such as repair, reuse, remanufacturing, refurbishment and recycling [8]. Within the context of battery system EoL activities such as remanufacturing, the battery's EoL performance evaluation requires careful consideration as testing requirements for the battery system for xEVs (that include Battery Electric Vehicles (BEVs) and Hybrid Electric Vehicles (HEVs)) differs significantly from traditional EoL testing for internal combustion engine (ICE) vehicles [9]. High level research for

automotive circular economy activities such as remanufacturing has already been undertaken extensively [10,11, 12, 13] and some work has been completed on the evaluation process [12, 14]. Currently, research have been focused on testing for new battery packs [15], [16] but very little research have been performed on the specific testing process for EoL xEV battery systems. It is vital to better understand the testing of these EoL batteries and have an optimized testing strategy in place to enable circular economy activities within the business. Although with previous research the focus was mainly on cell level testing [17, 18, 19, 20, 21] for automotive energy storage systems, with some research into the parallel [22] and series connections [23] between cells in the modules, relatively little research have been performed at a modular level [15, 16]. Some of the advantages of working on a modular level include:

- If packs can be dismantled and only faulty modules sent for repair, less weight will need to be moved leading to lower transport costs. This will also lead to a cost benefit due to less packaging being required that has to be UN approved according to the Accord Dangereux Routier (ADR) regulations stipulated in [24].

- Moving lower voltage modules compared to the High Voltage (HV) packs require significantly less safety precautions.
- If a module is tested and fails, only the module would have to be sent for recycling instead of the whole pack which would reduce recycling cost significantly for the responsible producer [25].

The current issue with testing of these modules from various manufacturers is the fact that there are various designs and no harmonization between the various designs. The differences in module design is further complicated by the three main form factors currently being deployed by automotive EV pack manufacturers which are the 18650 cylindrical cell used in the Tesla model S [26], the pouch type cells used in the Nissan Leaf [27] and the prismatic cell used in the Mitsubishi i-MiEV [26]. Thus in this paper practical considerations when electrical tests are performed were also considered and investigated through systematic teardown activities of the modules.

International standards and best-practice guides exist that reports the performance evaluation of both EV and HEV battery systems [12], [28, 29]. However, a common theme is that the test duration can be excessive and last for a number of hours as highlighted in [30]. The aim of this research is to address the need for optimized module level tests that requires less time whilst understanding the link between time and accuracy compared to standards such as IEC-62660 and ISO-12405.

In the research presented herein the authors assess whether energy capacity and impedance measurements of Li-ion modules currently on the market can be accelerated; reducing the test duration to a value that may facilitate further EoL options. Experimental results for capacity, Pulse Power Test (PPT) and multisine internal resistance measurements (defined and discussed in [31, 32]) are presented. These results would enable organizations that test used Li-ion modules for different EoL applications to prioritize the importance of test accuracy versus experimental test time resulting in optimized testing in either distributed or centralized circular economy activities.

BACKGROUND

A Circular Economy (CE) (Figure 1) is an industrial system that is restorative or regenerative by design and aims to move away from traditional linear system (make, use, dispose). Adopting this approach can be measured using the Triple Bottom Line (TBL) metrics which encompasses economic, environmental and social benefits. The system will facilitate retaining key resources within the supply chain for longer, extracting maximum value from them before regenerating products and materials at the end of their service life [33]. Benefits includes an estimated annual saving of between €465 - 565 billion in the EU if a circular economy was achieved in relevant manufacturing sectors [34]. Included in this is the automotive industry, which is showing increased momentum towards adopting CE principles within the EV market [35].

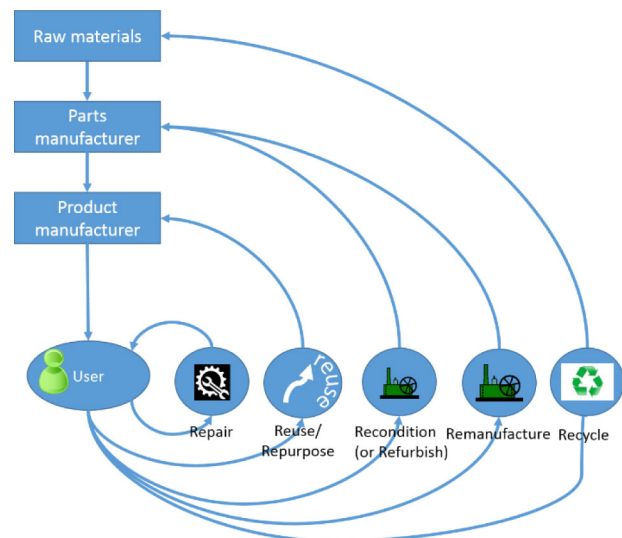


Figure 1. The circular economy [36].

An example of the various circular economy activities for a traction battery system is shown in Figure 1 and includes repair, reuse in the same application or repurposing for a different application, reconditioning or refurbishing, remanufacturing and recycling. A common requirement for all the mentioned circular activities, to support which route is the optimal choice, is to be able to determine the state of the battery. Throughout the lifecycle, each stage requires testing of the battery cell/module/pack for the relevant stakeholder to be able to verify and identify the State-of-Health (SoH) and State-of-Charge (SoC) of the Lithium-ion battery (LiB). The term SoC, which is a measure of the energy contained in the cell as a percentage of the total energy capacity of the cell. The health of the battery measurement is referred to as the SoH and determines the current condition compared to when the battery was new.

EV pack design varies significantly across different automotive pack manufacturers in terms of chemistry, form factor and cooling strategy. The preferred battery of choice for use in EVs is LiBs [37] due to their high energy density, reduced weight and long lifespan [38]. The parts within an EV battery pack can generally be split into four high levels: sub-assemblies, electrical components, structural components and the thermal management system. The sub-assemblies (or 'sub-packs') contain a number of modules, which in turn contain a number of cells. Outside of the sub-assemblies the pack contains other electrical components such as the Battery Management System (BMS), HV wiring and various power distribution equipment. To keep all components secured, structural components are required throughout the pack, including enclosures and supports. Finally, a battery pack may also contain a thermal management system to keep components, particularly the modules and cells, within a certain temperature window. Thermal management systems include liquid-cooled or air-cooled types.

To ensure the optimum EoL strategy in terms of environmental impact and financial cost is identified, a clear understanding of the factors that degrade the cell capacity are needed. Several studies highlight the importance of cell operating temperature and energy throughput resulting in an increase in impedance and a decrease in

capacity [39, 40, 41, 42, 43]. The effect of temperature on the module can have a negative impact for both high and low temperatures [43]. The link between relaxation time and capacity has also been studied [44] and shows capacity increase with an increase in relaxation time. Based upon a better understanding of battery degradation, the decision threshold for EoL batteries can be discussed. The authors in [45] highlighting different EoL scenarios identify remanufacturing as the optimal choice for EoL for a battery with a capacity between 80-100% as shown in Table 1.

Table 1. SoC and impedance ranges for various Li-ion EoL scenarios (Compiled from [9, 45]).

EoL Scenario	% Remaining capacity relative to new battery capacity
Repair	80%-100%
Reuse	45%-80%
Refurbish	45%-80%
Remanufacture	80%-100%
Recycle	Below 45%

For battery with a retained capacity of between 45% and 80%, re-use within grid storage is identified as the best EoL option. Below the 45% threshold, material recovery through recycling will yield greatest economic benefit. In the automotive industry the general consensus is that a traction battery of an xEV at EoL still has 70%-80% retained capacity compared to new. The tests utilized in circular activities in the reverse logistics chain discussed in [36] have varying mechanical testing requirements at the different stages within the lifecycle but have the same electrochemical requirements, namely the immediate SoC of the cell and the SoH of the cell.

In order to fully investigate the SoH of a cell both the impedance and capacity of the cell need to be quantified. The impedance and capacity performance parameters can be traced back to previously defined tests for Li-ion cells in 18 international test standards [28, 46].

Current Testing Standards

Current testing standards for capacity measurement of Li-ion cells (i.e. IEC-62660 and ISO-12405) would require at least a test duration of circa 10 hours as highlighted in Figure 2(a) to complete performance tests (which consist of a thermal stabilization phase, SoC adjustment phase and a discharge phase) shown in Figure 2(b).

Such an excessive test duration when considering large volume testing in a reverse logistics scenario, coupled with the expected rise in EV sales volumes to 11 million globally by 2020 [49], would be prohibitive for a number of vehicle manufacturers and specialist suppliers to apply Circular Economy principles within their businesses. Several publications have addressed the excessive test durations [30,36,50] with the focus primarily on cell level testing [30] and model parameter estimation [50]. Research in this paper has focused on module level test duration reductions for commercial EoL testing in circular economy activities.

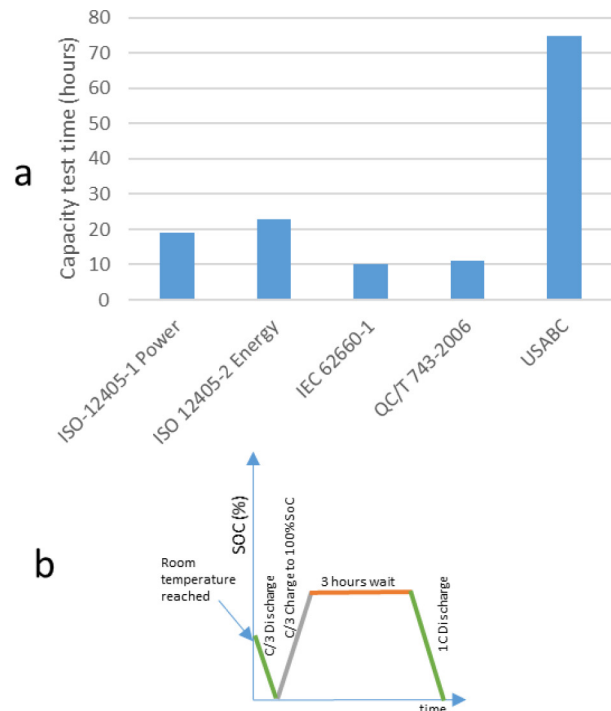


Figure 2. (a) Capacity test duration for various mainstream standards. Compiled from [28, 46, 47, 48]. (b) Typical capacity measurement profile based on IEC-62660 standard.

Internal Resistance Measurement Methods

Various internal resistance measurements exist such as DC current pulse and AC electrochemical impedance spectroscopy (EIS) methods [51]. The two measurement methods for internal resistance tests employed for this paper include the PPT and the multisine test. The PPT test was mainly selected due to being included in the mainstream standards. The multisine internal resistance measurement was mainly selected for its short test duration (circa 98% shorter compared to PPT with 30 minute wait periods between 10 pulses) [31, 32].

The PPT profile consists of 10 pulses, 5 discharge pulses and 5 charge pulses with a wait time varying from 10 minutes to 30 minutes between pulses depending on the specific Device Under Test (DUT) requirements. The PPT results were calculated from the 5 discharge pulses applied at 50% SoC at 25°C. The PPT method utilised in this paper is based on the PPT defined in IEC-62660. A single pulse is applied for 10 seconds with a wait time of 30 minutes between each pulse. In order to calculate the internal resistance (R_{int}) of the cell, the 10th value (the 10 second pulse was sampled every second resulting in 10 measurement points for each pulse) of the cell voltage was recorded at the end of the pulse as shown in Figure 3(a). Using the voltage values and corresponding discharge pulse current values the internal R_{int} is calculated using a linear regression method. Equation 1 was used to calculate R_{int} .

$$R_{int} = \frac{n \sum_{i=1}^n x_i y_i - \sum_{i=1}^n x_i \sum_{i=1}^n y_i}{n \sum_{i=1}^n x_i^2 - (\sum_{i=1}^n x_i)^2}$$

For equation 1: x = applied pulse current, y = voltage value and n = number of pulses (equal to 5 discharge pulses or 5 charge pulses). The calculated R_{int} value corresponds to the R_{int} value in the Equivalent Circuit Model (ECM) shown in Figure 3(b).

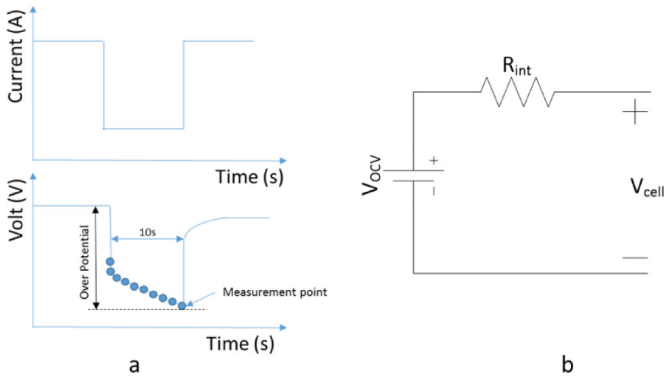


Figure 3. (a) PPT 10 second pulse (b) Basic ECM for a battery.

The ECM equation 2 is:

$$V_{cell} = V_{OCV} - I * R_{int} \quad (2)$$

with V_{cell} the cell voltage, V_{OCV} the open circuit voltage, R_{int} the internal cell resistance and I the cell charge/discharge current. The PPT test procedure, though easy in design, is limited in bandwidth and amplitude as a current signal for Li-ion ECM modelling. For a 10s PPT pulse 90% of the signal power is contained within 100 mHz; as such a pulse signal insufficiently spans the frequency spectrum when compared to a drive cycle, which usually spans up to 1 Hz (see Figure 4(a)), when used for model validation.

A multisine signal is in comparison more dynamic in both amplitude and frequency. The signal consists of five design parameters (which include pulse amplitudes-same as for the PPT, wait interval lengths and scaling factors) and is designed by super-positioning a low frequency base-signal (drive cycle) and high frequency random phase multisine [31, 32]. Both amplitude and bandwidth can be excited similar to a drive cycle and the signal is therefore more relevant for model parameter estimation.

For the multisine test, the design signal (like the one shown in Figure 4(b)) is repeated 5 times, thus giving the signal five periods. The first period is ignored due to being in a transient state and the last four periods used to estimate an impedance value. Five periods were chosen to ensure the cell was not heated up significantly. More details about the multisine signal being mapped to a ECM can be found in [31]. The value used as the multisine resistance value is the real value corresponding to R_{int} in equation 2.

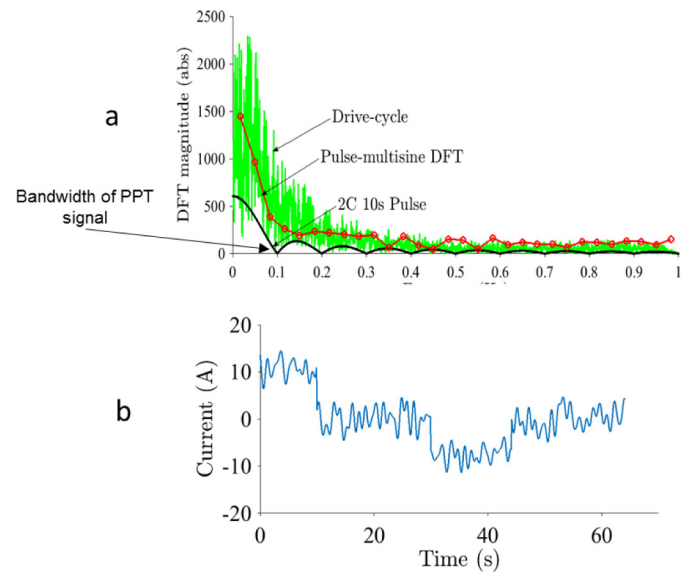


Figure 4. (a) Discrete Fourier Transform (DFT) magnitude comparison of a drive-cycle, a 10s pulse and multisine. The magnitude of the multisine is seen to follow the spectrum of the drive-cycle. (b) An examples of a multisine signal.

The parameters for the capacity and impedance test methods utilised in the experiments are discussed in more detail in the methodology section.

Taking into account the aims of economic and environmental benefits for circular economy activities, the underlying requirement to determine the EoL battery's SoH and the lengthy standard testing, the remainder of the paper will be focused on accelerated electrical testing for traction battery modules. This paper is structured as follows: The first section is a discussion of the methodology followed in the electrical testing experiments. The second section contains the results which investigates the variation in capacity and internal resistance tests for commercially available modules from BEV and HEV battery systems when tests are accelerated by increasing recommended test C-rates and wait times. The third section contains the analysis of the data and the fourth section the discussion. The last section discusses the main conclusions and further work.

METHODOLOGY

Module Selection

Two module types were selected for evaluation as part of this research; a *power module* from a Porsche Panamera S Plugin-HEV (PHEV) and an *energy module* for use within a Tesla Model S BEV. Table 2 presents the pertinent electrical performance data and physical parameters for each module.

Apart for the electrical testing of the modules it is important to consider the practical considerations when electrical tests are performed. Figure 5 shows the complete Porsche and Tesla modules, the outer casings and the individual cells of each of the modules. The