On the requirements of the power converter for second-life lithium-ion batteries

Alberto Berrueta, Idoia San Martín, Julio Pascual, Pablo Sanchis and Alfredo Ursúa
DEPARTMENT OF ELECTRICAL, ELECTRONIC AND COMMUNICATIONS ENGINEERING,
INSTITUTE OF SMART CITIES, PUBLIC UNIVERSITY OF NAVARRE
Campus de Arrosadía, 31006
Pamplona, Spain
Phone: +34 948166069
Email: alberto.berrueta@unavarra.es
URL: http://www.unavarra.es

Acknowledgments

We would like to acknowledge the support of the Spanish State Research Agency (AEI) and FEDER–UE under grants DPI2016-80641-R and DPI2016-80642-R and of Government of Navarra through research projects PI020 RENEWABLE-STORAGE and 0011-1411-2018-000029 GERA.

Keywords

≪Automotive component≫, ≪Battery Management System (BMS)≫, ≪Electric vehicle≫, ≪Life cycle analysis (LCA)≫, ≪Multilevel converters≫.

Abstract

The use of lithium-ion batteries is increasing year after year, especially in the automotive sector. Given the high requirements of electric vehicles, their energy storage systems are discarded when they still have around 70% of its initial capacity. These discarded batteries are being studied as a low-price option for stationary systems, mostly related to renewable energy generation, with lower battery requirements. However, the increasing dispersion of cell capacity detailed in this contribution limits the use of second-life cells if regular battery management systems and power converters. We present in this contribution an experimental comparison of the capacity dispersion between fresh and second-life cells, and detail the relationship between the capacity dispersion and the required BMS functionality. Furthermore, we include the ageing phenomena in the analysis by means of experimental ageing results, given that the capacity dispersion is enlarged as the battery ages. After this, we use this data to quantify advantages and disadvantages of a combined BMS and power converter, based on a multilevel topology, compared to a conventional BMS. The most relevant result, when a 55-cell battery is analysed, is a 65% increase in capacity during its whole second life if the BMS and power converter are combined by means of a multilevel topology. The increased level of complexity required by the combined BMS-power converter architecture is analysed in this contribution, providing a convenient tool for the selection of the most suitable option for each application.

Introduction

Nowadays, the mobility is based on combustion vehicles, which entail greenhouse-gas emissions and unhealthy gases in the cities. Since some years ago, important political and industrial efforts are headed towards the electrification of the automotive float. As a result, the electric vehicle (EV) market is exponentially increasing year after year. The International Energy Agency (IEA) reports annual growing rates larger than 50% from 2013 to 2017, reaching a market size of 1 million EVs sold in 2017 [1]. This exponential growth is expected to be maintained during the following years.

The Li-ion battery is a main component of EVs. An increasingly-common scenario is the disposal of these batteries after their use in an EV. Battery recycling is a costly process and, therefore, other alternatives are arising to deal with them. One of the most interesting options is to give the batteries a second life in a less demanding application [2].

The degradation of a Li-ion battery has two main consequences [3]. On the one hand, the amount of energy that the battery can store (capacity) is reduced as a consequence of a reduction of the battery active material (either because of irreversible electrochemical reactions or because of a mechanical degradation of the electrodes). On the other hand, a passivating layer called solid-electrolyte interface (SEI) grows on the interface between the electrodes and the electrolytes, specially on the anode, which hinders the movement of lithium ions across the battery, increasing the energy losses (impedance rise). This issue has two main consequences: a lower cycle efficiency and an increased thermal power that needs to be evacuated from the battery [4].

EV users demand high-capacity batteries in order to preserve the driving range, as well as high-power batteries to keep the acceleration and high power charging capability. Therefore, when the battery capacity decreases down to 70 to 80% of its initial value, the vehicle battery is replaced [5]. A second use of these batteries for less demanding applications, mainly stationary applications such as self-consumption systems or grid support at utility scale, represents a good chance to extend the use of these batteries, thereby increasing their profit before recycling. However, the poor performance and inhomogeneity of these discarded battery cells prevent their proper exploitation unless a careful analysis of the power electronics and battery management system (BMS) is accomplished.

This contribution aims at the quantification of the achievable benefits, shedding light on potential research topics on the edge between battery systems and power electronics. With this purpose, 60 battery cells discarded from real electric vehicles are characterised and compared with a set of fresh cells in order to quantify their second-life characteristics and dispersion. Based on this characterisation, we analyse the potential of alternative power converter topologies, based on modular multilevel converters (MMC), that allows a full utilisation of disperse cells in a battery. Given the homogeneity measured in fresh cells, the benefits of these topologies are not worth it in first-life batteries. However, traditional power converters do not allow a proper exploitation of the heterogeneous second-life cells, arising the interest of alternative options. Finally, we make a summary of the conclusions, showing the main ideas in Table I.

Characteristics of second-life lithium-ion cells

In order to characterise a sample of cells X, the statistical variables that are used in this contribution are the sample mean ($\overline{X}$) and the dimensionless coefficient of variation (CV_X), which is defined based on the sample mean and standard deviation (s_X) as follows:

$$CV_X = \frac{s_X}{\overline{X}} \tag{1}$$

The manufacturing tolerance of Li-ion cells is relatively tight, as shown in Fig. 1 (a) and (b). The average capacity of the studied fresh cells is $\overline{C}_{fresh} = 31.6$ Ah, and the coefficient of variation is $CV_{C_{fresh}} = 3.8 \cdot 10^{-3}$. However, the cells used in EVs suffer from inhomogeneous ageing mechanisms . EVs are used in diverse climatic regions, with different driving profiles and charged with particular frequency and charging method. Moreover, the batteries are not replaced when they have run the exact same number of cycles. Even more, the cells of a single battery pack undergo different ageing mechanism, mainly due to temperature gradients inside the battery pack. This leads to inhomogeneous battery packs, which is harmful for its proper operation [6] Fig. 1 (c) represents the capacity of the 60 cells removed from EVs. Among them, there are 5 cells with capacity values well below the others, which are treated as outliers and, therefore, removed from the sample for further analysis. The average capacity of the cells has been reduced from $\overline{C}_{fresh} = 31.6$ Ah to $\overline{C}_{used} = 22$ Ah, which represents a 73% remaining capacity. As shown in Fig. 1 the dispersion of these values is also higher, reaching a value of $CV_{used} = 1.87 \cdot 10^{-2}$.

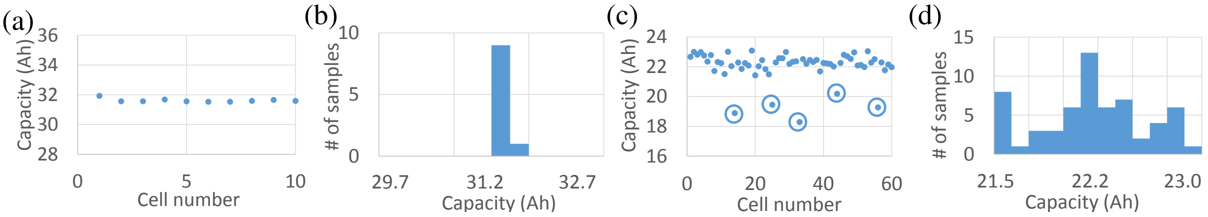

Fig. 1: Dispersion of the main characteristics of fresh and used automotive cells: (a) capacity of 10 fresh cells, (b) dispersion analysis of the capacity of fresh cells (c) capacity of 60 used cells with five circled outliers, and (d) dispersion analysis of the capacity of used cells.

However, the dispersion of second-life cells removed from vehicles is not the most critical factor, given the fast enlargement of this dispersion when used for a second life application. In order to quantify this issue, accelerated ageing experiments are being carried out in the Energy Storage Laboratory, at the Public University of Navarre (UPNA). Fig. 2 (a) shows a picture of this laboratory, in which two climatic chambers and three battery testers are used for a controlled ageing of several Li-ion battery cells discarded from actual electric vehicles. These equipments control ambient temperature and charge–discharge current and voltage. The accelerated ageing experiments consist on continuous charge–discharge full cycles, each of them with CC–CV charge at a current rate of 1C up to 4.15 V per cell, followed by a CV phase down to a current of 0.05C, and a 1C CC discharge down to 3 V. The ambient temperature is controlled at 25±2 °C during the whole duration of the experiment.

Fig. 2 (b) shows capacity measurements during these ageing experiments performed with eight of the cells from the sample X_{used}. Given that, after more than 700 charge–discharge cycles, the end of life (EOL) of the cells has not been reached, the experiments are currently ongoing in the laboratory. Even though the experiments are not finished, the increasing capacity dispersion among the cells can be appreciated. The difference between maximum and minimum capacity at the beginning of the test was 2.8 Ah, while 700 cycles later, this range has increased up to 3.5 Ah, which means a 25% increase. The coefficient of variation, CV, has suffered an increase of 35% during these 700 cycles.

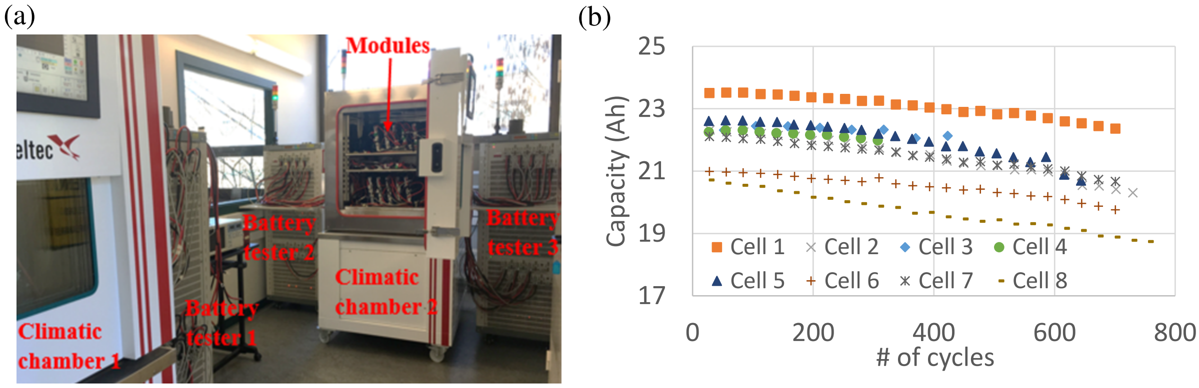

Fig. 2: Experimental work performed at the Public University of Navarre: picture of the Energy Storage Laboratory (a) and capacity measurements during ageing experiments performed with eight battery cells discarded from electric vehicles (b).

This increasing dispersion among cells is due to the accelerating ageing rate suffered by Li-ion batteries as their state of health (SOH) approaches the end of life. Some ageing processes, such as the electrode passivation and the loss of active material, are self-accelerating phenomena, leading to faster battery ageing. Assunção et al. presented a work characterising the full degradation of battery cells discarded from electric vehicles and found a trend such as the one depicted in Fig. 3 (a) [7]. The capacity of the 55 cells represented in Fig. 1 (a) (outliers excluded) at the beginning of their second life ranges from 21.4 to 23.1 Ah, which is coloured in orange in Fig. 3 (a). Note that the vertical dimension of the rectangle represents capacity dispersion. Based on the results published in [7], as the cells are used in a second-life application, they loose capacity at an accelerated rate.

Given that all the cells are of the same type, the variety of capacity measured among the cells represents different SOH levels. The horizontal dimension of the orange rectangle in Fig. 3 (a) accounts for the different number of equivalent cycles that the analysed cells had suffered during their first life in an electric vehicle. The ageing of this group of cells can be represented in the graph as a moving rectangle with a constant horizontal dimension (given that second-life cells are cycled in a uniform way) and augmenting vertical dimension, due to the accelerating ageing mechanisms.

For instance, the yellow rectangle in Fig. 3 (a) represents this situation after 2500 cycles of second life use. The cells with highest capacity would keep 82% of the second-life capacity, while the cells with lower capacity would only keep 28%. Provided that cells are connected in series, as shown in Fig. 3 (b), to build a battery, the usable capacity is limited by the cell with lowest capacity. In other words, after 2500 cycles of second-life application, the battery can only store 28% of the initial capacity, even though some cells have a remaining capacity of 82%.

$$C_{bat}\,[\mathrm{Ah}] = \min_{i=1\ldots n} C_i \tag{2}$$

$$E_{bat}\,[\mathrm{Wh}] = C_{bat} \cdot v_{bat} \tag{3}$$

(a)

(b)

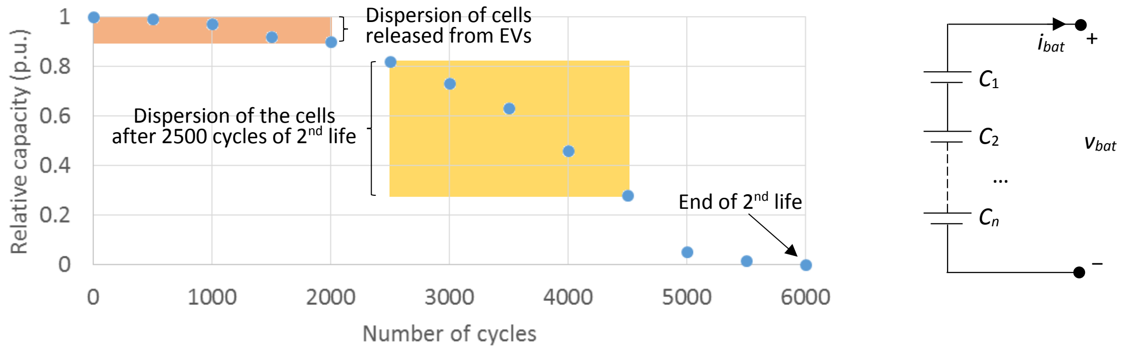

Fig. 3: (a) Capacity fade of a reused cell after disposal from a vehicle based on previous studies. The capacity fade is accelerated as the number of cycles increases. Data from [7] and (b) schematic of n cells connected in series.

Actually, the ageing measurements shown in Fig. 2 (b) confirm this trend. The capacities of the cells at the beginning of the test differ in around 10%, in accordance to the orange rectangle in Fig. 3 (a). After 700 cycles, the remaining capacities are between 80 and 97% of the maximum initial capacity, as predicted by Fig. 3 (a).

This increasing variation is the main reason why the battery capacity, lifetime, and, therefore, profitability can be enlarged if used with an integrated cell-level battery management system and power converter (BMS-PC) able to obtain the most of each cell (preserving the other cells from undesired damages). By contrast, conventional BMSs and PCs for first-life batteries control and optimise the performance of the whole battery pack, which is a valid and cheaper approach providing that the cells have similar characteristics.

Combined cell-level BMS-PC

A BMS is an electronic circuit used to manage a battery. This device has various functionalities of capital importance for the safe operation of a Li-ion battery:

- Measurement: cell voltage and battery temperature and current.
- Management: protection of the battery, thermal management and cell balancing.
- Evaluation: estimation of state of charge (SOC), depth of discharge, state of health, capacity and resistance of the battery.
- External communications with other devices or with humans.

From the above-mentioned functions, we study herein the cell balancing, given its interest for second-life batteries built by cells such as the ones described above, and its potential to be integrated with the battery PC.

Cell balancing in a conventional BMS

Due to manufacturing tolerance, Li-ion cells have different self-discharge currents, which leads, in the long term, to a dispersion of the cell voltages and SOC [8]. As explained above, this is a handicap for the full usage of the battery capacity. Therefore, a conventional BMS, designed for fresh, homogeneous Li-ion batteries, includes a balancing circuit, such as the one shown in Fig. 4 (a). The battery needs to be balanced when a large dispersion in the cell voltage is detected. To do so, the battery is moved to idle state and a small current (around 10 mA) is drawn from the cells with highest voltage across balancing resistors (R_{bal}).

Fig. 4 (b) shows measured cell voltages during a balancing process of a 6-cell stationary battery. The voltage dispersion before the balancing is 23 mV and, after a 2-hour balance, it is reduced to 5 mV. This process is suitable for a battery built by fresh cells, which requires sporadic and minor balance processes, but does not allow the proper exploitation of second-life batteries. On the one hand, the balancing speed required by second-life batteries is much faster than the 2 hours shown in Fig. 4 (b), and, on the other hand, if the energy dissipated in the resistances R_{bal} is large enough it may be worth it to be used for the battery operation.

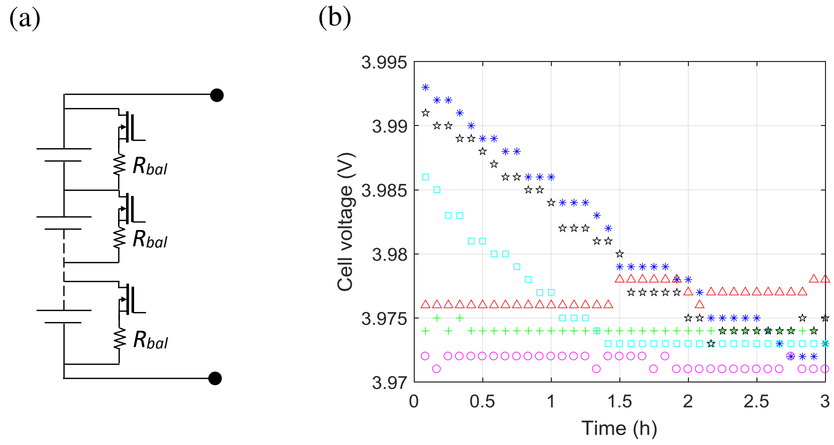

Fig. 4: Typical balancing of Li-ion batteries: (a) circuit schematic of a conventional balancing system, and (b) measured data of a balancing process of a 6-cell battery.

Integrated balancing and cell-level power conversion

This approach of individualised cell charge management consists of a battery that allows the individual control of the power managed by each of the series-connected cells. The most typical approach to do so is a multilevel structure, such as the one shown in Fig. 5 (a) [9]. Note should be taken that the switches drawn in Fig. 4 (a), typical from conventional BMSs, are signal switches that manage currents of a few milliamps. By contrast, the ones shown in Fig. 5 (a) are power semiconductors that need to manage the whole battery current.

The main advantage of this idea is that it allows a full utilisation of the energy stored in the battery, avoiding the limitation imposed by the cell with lowest capacity. Fig. 5 (b) shows the amount of energy that can be used with each of the two BMSs in a battery built by the series connection of the 55 cells studied in this contribution. For the sake of comparability, the magnitude is normalised by the initial capacity of the battery. It is seen that the advantage of the individual charge management is negligible at the beginning of the second life. However, as the cells age and the degradation rate increases, the usefulness of such an assembly becomes noticeable. During the whole second life of the battery, the typical BMS and power converters used for first-life batteries reduce the utilisation of the battery down to 65% as compared with an individual charge management strategy, as represented by the green area in Fig. 5 (b).

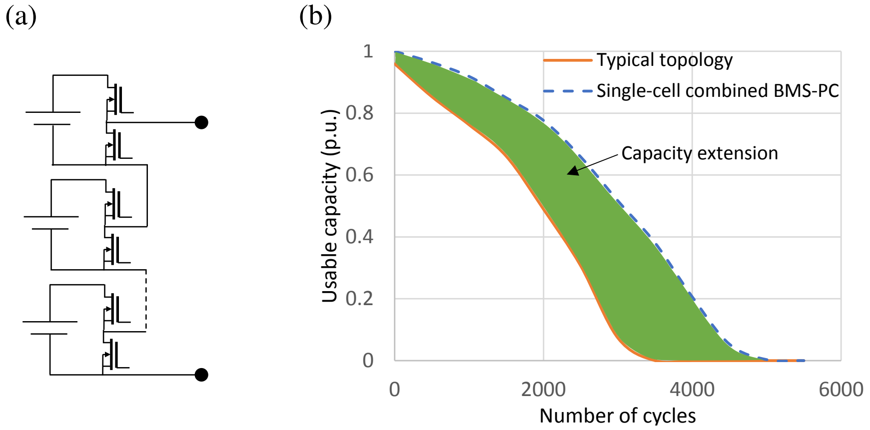

Fig. 5: Individual charge management: (a) half-bridge converters for individual cell charge management, and (b) comparison of the usable capacity as a second-life battery built by 55 cells ages.

It is remarkable to note that the battery voltage depends on the number of voltage levels that are connected at a time. As a consequence, the number of cells that are used cannot be arbitrarily chosen. This is the reason why the performance of the cells needs to be carefully analysed in order to design a competent management algorithm that achieves their full charge and discharge when required. Related to this multilevel topology, an interesting approach is to cluster a reduced number of cells to build each voltage level of the MMC. Such an assembly requires the voltage measurement of each cell, as well as balancing circuits in order to overcome the charging deviations brought by uneven self-discharge currents. The drawback of an increased number of cells per voltage level is that the dispersion among the cells of a single level do not allow the individual control of each cell. Therefore, a trade-off between usable capacity and MMC complexity needs to be found for large-format batteries.

Conclusion

The dispersion of the cell capacity has been identified as a main issue for the design and management of second-life batteries after their disposal from electric vehicles. Typical BMS boards and power converters used for regular batteries are developed technologies. However, the specific requirements of second-life batteries related to these two elements have not been properly analysed in the literature. A characterisation of 60 cells that have been removed from electric vehicles because they reached their end-of-life criteria is presented in this work, and their main characteristic (capacity dispersion) is compared with a group of the same kind of cells that are in new conditions (fresh cells). Remarkable differences have been quantified by means of the coefficient of variation: $CV_{used} = 1.87 \cdot 10^{-2}$ while $CV_{fresh} = 3.8 \cdot 10^{-3}$. This augmented dispersion between cells suffer a noticeable increase during the second life of the battery, given their increasing degradation rate. This increasing dispersion has been experimentally measured by means of eight ageing experiments. In this situation, an augmented complexity and price of the power electronic converter connected to the battery may worth its value in a better utilisation of its capacity. Actually, only 65% of the remaining battery capacity can be used during its second life if traditional BMS and PC are used, while the integrated cell-level BMS-PC can harvest its total capacity, as stated in

Table I. Advantages and disadvantages of typical and combined BMS-PC are identified along this work and summarised in Table I.

Table I: Main characteristics of the studied BMS and power converter alternatives.

	Typical BMS and power converter for first-life batteries	Cell-level combined BMS-PC
Supplementary components	DC/AC power converter	—
Semiconductors per cell	1	2
Switching current	mA	Battery current
Switching frequency	0	kHz
Switching voltage	5 V	5 V
Time at idle state (balancing)	One hour / week	Not required
Capacity use 1^{st} life (50 cells)	0.95	1
Capacity use 2^{nd} life (50 cells)	0.65	1

The main differences between both architectures are divided into four levels. Firstly, as stated in the first row of the table, if the BMS includes the PC no power converter is required for the grid connection of the battery. Secondly, the required semiconductors are different for both architectures. The main difference is that the typical BMS has a low-power mosfets per cell that drives a current in the range of milliamps and is turned on and off when a balancing process is required. By contrast, a combined BMS-PC requires two semiconductors per cell able to drive the whole battery current switching at a frequency typical from power converters. Thirdly, the operation of the battery with these two architectures differ in two main aspects. A battery with a typical BMS requires around one hour per week at idle state in order to balance its cells, which can be a handicap in some applications. These balancing processes are not needed with a combined BMS-PC. Finally, the usable capacity of any battery with a BMS-PC architecture is the full batter capacity, represented in the two last rows of Table I by the number 1. Meanwhile, a typical BMS allows for a 95% utilisation of a first-life battery, which is a convenient percentage for most applications. However, the maximum capacity that can be used from a second-life battery with 50 cells is 65% of the total battery capacity, thereby limiting the use of traditional BMSs with second-life Li-ion batteries.

The analysis presented in this contribution quantifies the technical advantages of the BMS-PC architecture when compared with a traditional BMS. The convenience of one alternative or the other will depend on the requirements of each application and on the cost of each solution.

References

[1] "Global EV outlook 2018," International Energy Agency, Tech. Rep., 2018.

[2] E. Martinez-Laserna, E. Sarasketa-Zabala, I. Villarreal Sarria, D. Stroe, M. Swierczynski, A. Warnecke, J. Timmermans, S. Goutam, N. Omar, and P. Rodriguez, "Technical viability of battery second life: A study from the ageing perspective," *IEEE Transactions on Industry Applications*, vol. 54, no. 3, pp. 2703–2713, 2018.

[3] A. Berrueta, J. Pascual, I. San Martín, P. Sanchis, and A. Ursúa, "Influence of the aging model of lithium-ion batteries on the management of PV self-consumption systems," in *2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I CPS Europe)*, 2018, pp. 1–5.

[4] A. Berrueta, A. Urtasun, A. Ursúa, and P. Sanchis, "A comprehensive model for lithium-ion batteries: From the physical principles to an electrical model," *Energy*, vol. 144, pp. 286 – 300, 2018.

[5] S. Saxena, C. L. Floch, J. MacDonald, and S. Moura, "Quantifying EV battery end-of-life through analysis of travel needs with vehicle powertrain models," *Journal of Power Sources*, vol. 282, pp. 265 – 276, 2015.

[6] M. Dubarry, C. Pastor-Fernández, G. Baure, T. F. Yu, W. D. Widanage, and J. Marco, “Battery energy storage system modeling: Investigation of intrinsic cell-to-cell variations,” *Journal of Energy Storage*, vol. 23, pp. 19 – 28, 2019.

[7] A. Assunção, P. S. Moura, and A. T. de Almeida, “Technical and economic assessment of the secondary use of repurposed electric vehicle batteries in the residential sector to support solar energy,” *Applied Energy*, vol. 181, pp. 120 – 131, 2016.

[8] A. Berrueta, I. San Martín, P. Sanchis, and A. Ursúa, “Comparison of state-of-charge estimation methods for stationary lithium-ion batteries,” in *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, 2016, pp. 2010–2015.

[9] J. V. Muenzel and D. Crowley, “Battery system,” Jul 2017, International Patent WO/2017/054049, Relectrify PTY LTD.