Analysis of the Remaining Useful Life of Electric Vehicle Batteries and Development of Second-Life Solutions

Aghatta Moreira[1](✉), Vitor Arioli[1], Maria de Fatima Rosolem[1], Raul Beck[1],
Camila Omae[2], Hongwu Ding[2], Thiago Nascimento[1], Fernando Padela[1],
Gustavo Contin[1], Marcelo Camboim[1], Jonathan Moura[1], and Thomas Nunes[1]

[1] Research and Development Center in Telecommunications (CPQD), São Paulo, Brazil
`amoreira@cpqd.com.br`
[2] CPFL ENERGIA S.A, Campinas, Brazil

Abstract. When batteries used in electric vehicles reach the end of their useful life in this application, they still have a high potential for reuse in other less demanding applications regarding power and cycling, such as stationary energy storage systems with renewable energy. This concept is called second-life. In this context, the pioneering Research and Development (R&D) project "CPFL Second-Life" of the Electricity Utility Company CPFL Energia is under development in Brazil, in cooperation with CPQD (Telecommunications Research and Development Center) and BYD Brazil. The objective is the development of energy storage solutions using second-life batteries. This article presents methodologies and main results obtained through the realization of this project, aiming to evaluate the actual performance of EV batteries in second-life. To this end, cell reconditioning and remanufacturing techniques are being developed and improved, from disassembly to reconfiguration in new systems, considering mechanical, thermal, electronic, and systemic developments necessary for this. Simultaneously, several laboratory tests are being carried out to characterize the remaining useful life of these batteries in second-use applications; both to understand their behavior and to support the development of algorithms, which will be used in new systems to monitor their main operating parameters and which will also identify the remaining lifetime given the future operating conditions of the batteries. The development of an energy storage solution from degraded cells during application in EVs used in the country will strengthen the technological advancement of the national EV and battery industry. Additionally, this project is fully aligned with the concept of circular economy, providing the reuse of elements that would initially be discarded or sent for recycling.

Keywords: Algorithm design and analysis · Battery management system · Data analysis · Electric Vehicles · Energy Storage · Lithium-ion batteries · Second life

1 Introduction

The transport sector is responsible for a quarter of global greenhouse gas emissions such as carbon dioxide (CO2), methane and nitrous oxide [1]. As a consequence, it is

P. Schossig et al. (Eds.): IRES 2022, AHE 16, pp. 308–321, 2023.
https://doi.org/10.2991/978-94-6463-156-2_21

undeniable that global decarbonization initiatives should be guided by the adoption of more sustainable means of transport to the detriment of dependence on fossil fuels. In line with this need, it is estimated that by the year 2030, the fleet of electric vehicles (EVs) in the world will reach 145 million units, representing, therefore, 7% of the total vehicle fleet in circulation [2]. This trend is driven by a series of circumstances, among which it is possible to mention the imposition of goals to limit the commercialization of traditional vehicles (with internal combustion engine) by several countries, such as China, the European Union and the United States, in addition, it is directly influenced by the downward trend in lithium-ion battery prices and greater access to charging infrastructures [3]. Along these lines, the expectation is that the final cost of EVs will continue to decrease, until their cost of acquisition is comparable to that of an internal combustion vehicle, which sustains the exponential growth of this market.

The battery chemistry most used today for the composition of EVs is lithium-ion (LiBs) due to its high energy density (from 200 to 250 Wh/kg) and satisfactory cyclic life. However, these batteries degrade during their use in vehicles as a result of two different aging phenomena, which in practice occur in combination, called Calendar Aging and Cycling Aging. Calendar Aging is the degradation that occurs in the battery even when it is in an open circuit condition, being affected by temperature and State of Charge (SoC) during its storage, that is, it consists of degradation due to self-discharge. Cycling Aging is the degradation by battery usage, often associated with the number of cycles completed by the battery, being dependent on temperature, SoC and depth of discharge (DoD) applied during its operation.

As a consequence of these degradation mechanisms, after being used in electric vehicles for periods of about 8 to 10 years, LiBs are no longer able to provide the minimum necessary autonomy and acceleration requirements, reaching the end of their useful life in this application. For this reason, even under optimistic estimates, it is expected that 3.4 million kg of LiBs previously used in EVs will be dumped in landfills by the year 2040 [4].

When removed from EVs, it is estimated that batteries still contain around 70–80% of their rated available storage capacity [5], which is enough for them to be reused in less demanding applications in terms of power and energy – this concept is called second life, and it consists of an alternative to fully exploit the use potential of these units, preceding the recycling processes. In line with this trend, Battery Energy Storage Systems (BESS) will be in strong demand in the next years, driven by a greater incorporation of Distributed Energy Resources (DERs) into the electricity grid.

For this reason, giving these batteries a second-life would be beneficial not only from an economic point of view, but would also help to reduce the global demand for batteries for application in BESS and reduce waste, which is extremely relevant given the increasing need for extraction of materials for the production of new batteries. In this context, the pioneering Research and Development (R&D) project entitled “CPFL Second-life” is under execution within the scope of National Electric Energy Agency (ANEEL) R&D Program by the Electricity Utility Company CPFL Energia, in cooperation with CPQD (Telecommunications Research and Development Center). The objective of the project is to develop energy storage solutions using second-life batteries. For this purpose, it

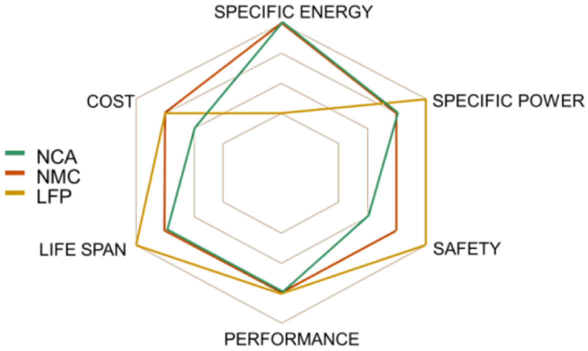

Fig. 1. Comparison of EV battery chemistries

includes the development of a battery disassembly process and a cell selection methodology, considering the need to recondition cells in new systems and all the mechanical, thermal and electronic developments associated with it. In addition, a series of laboratory tests are being carried out in order to allow the analysis of the useful life of these batteries when used in specific operating conditions adopted in new applications. From these tests, it is also intended to obtain subsidies for the development of algorithms to monitor the main battery operating parameters in the new application. From this, it is expected to fulfill necessary safety requirements and develop an algorithm to estimate the battery's Remaining Life Life (RUL) in real-time, given current operating conditions.

This article seeks to present the methodologies conceived and the main results obtained during the realization of this project in order to evaluate the real performance of second-life batteries. To this end, the work was divided into the following sections:

a) Chapter 2: Characterization of second-life cells received for analysis and disassembly procedure;
b) Chapter 3: Initial tests and cell selection methodology;
c) Chapter 4: Results of cycling tests carried out considering suitable applications for second-life batteries;
d) Chapter 5: Description of the developed BESS and embedded algorithms;
e) Finally, Chapter 6 gathers the final considerations.

2 Characterization of Received Cells

Lithium-ion cells are composed of a variety of elements, including the cathode, anode, electrolyte and separating membrane. The most relevant technological impact on its specifications is caused by the chemistry applied to its cathode - being the subject of several research and developments in the area. For this reason, the different commercially available battery cells are named after their cathode composition. With regard to batteries used in EVs, three chemistries stand out, as described in Fig. 1: LFP (Lithium Iron Phosphate), NMC (Lithium Manganese Cobalt) and NCA (Lithium Nickel Cobalt).

These cells differ in their key requirements, so the most suitable one must be chosen considering the operating criteria of each specific type of vehicle. LFP batteries are

Table 1. Description of the parameters of the analyzed lithium-ion batteries

Parameter	**Specification**
Chemistry	LFP
Capacity (Ah)	270
Nominal Voltage (V)	3,2
Limit charge voltage (V)	3,6
Final discharge voltage (V)	2,0
Recommended charge/discharge current (A)	54,0

cheaper, safer and have a longer cycle life compared to others, however, they have lower energy density – for this reason, their main applications are heavy EVs. On the other hand, NMC cells are used in popular light EVs, such as the Nissan Leaf and Mercedez-Benz EQS, and NCAs are applied in EVs with a focus on autonomy, such as the Tesla Model 3, Model Y, Model S and Model X [6].

The “CPFL Second-Life” project started in December/2019 and has an expected duration of 36 months. In order to evaluate the actual performance of second-life EV batteries to further develop energy storage products, more than 500 samples of LiB cells with the specifications described in Table 1 were analyzed.

2.1 Dismantling Process

The units available for analysis during project execution consisted of second-life battery modules. As the objective is to analyze the cells separately, these modules had to be dismantled. At the moment, there is no national regulation that addresses the procedure for dismantling EV batteries for reuse. Due to the characteristics of the module studied and considering the equipment available in the laboratory, this process required manual work by specialized technicians in order to execute it safely. Figure 2 describes the steps adopted by CPQD to dismantle the modules.

In the future, automated disassembly can contribute to the reduction of risks related to the handling of high voltage equipment and also reduce costs related to the process, since it is time-consuming. For this, there is a need for standardization in the packaging of batteries from different manufacturers. As an alternative, the possibility of developing technologies based on cloud computing capable of organizing the necessary steps for disassembling modules based on data found online has been studied in [7].

3 Cell Selection Methodology

To determine the actual capacity of the cells received to enable comparisons to be made between alternative methods of determining the State of Health (SoH) of second-life batteries, capacity tests were performed. With the cell fully charged and after a rest period of 1h to 4 h, a C5 discharge with constant current is applied, which is interrupted when the cell voltage reaches 2 V (Final discharge voltage – Table 1).

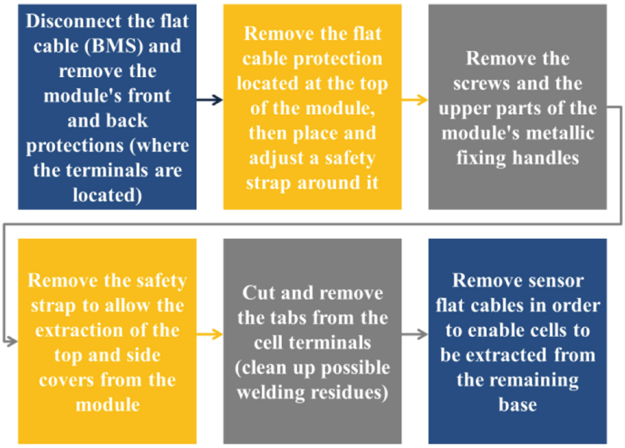

Fig. 2. The dismantling process is shown in a flowchart

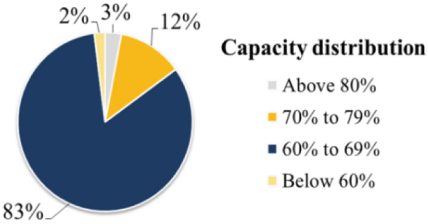

Fig. 3. Capacity of 395 samples

Figure 3 compiles the obtained capacity results, from which it was possible to observe a predominance of cells with capacity around 60% of the nominal. Despite this, there are cells from different groups of capacities, which is quite useful when considering useful heterogeneity criteria to enrich the studies, allowing comparisons of these values with other parameters, such as internal impedance. These analyzes are essential for the development of a robust methodology for faster cell selection, being an alternative to commonly applied capacity tests.

Essentially, SoH is a metric used to define the current state of the battery by comparing it to its ideal operating state. A cell's ability to store energy and provide power decays over time, due to internal chemical processes that lead to its degradation. For this reason, in addition to remaining capacity tests, analysis of resistance and possible internal degradations that could result in power loss must be performed.

The main degradation mechanism of the lithium battery is the growth of the solid electrolyte interface (SEI), a layer formed between the anode and the electrolyte. Other important mechanisms are: lithium plating (formation of metallic lithium), corrosion of the current collector and mechanical failure. Capacity loss is mainly caused by the irreversible loss of lithium ions and reactive material. Power Fade is caused by the kinetic increase of the cell's internal resistance [8].

There are a variety of techniques described in the literature for estimating the remaining LiBs capacity. The most common experimental methods are Ah Counting (also called Coulomb Counting), performing resistance or impedance measurements, and Electrochemical Impedance Spectroscopy (EIS):

a) **Coulomb Counting:** is the most common technique for determining SOH. Consists of subjecting the battery to charge and discharge cycles under specific conditions [9]. As this technique consists of performing tests that require the battery to be cycled between 0–100% SoC, it is very time consuming, being unfeasible when considering large amounts of batteries being removed from EVs;
b) **Resistance or impedance measurements:** impedance or resistance can be used as criteria for pre-selection of viable cells for reuse according to procedures detailed in UL 1974 - Standard for Evaluation for Repurposing Batteries;
c) **Electrochemical Impedance Spectroscopy:** This technique is already well established, being widely used in the laboratory to study internal chemical processes of degradation of lithium-ion cells. Differentiation between several different processes is made from the application of a low amplitude AC signal in a wide frequency range [10].

Among the techniques mentioned above, the EIS measurement is faster than the Coulombs Count, in addition to not requiring the battery to go through complete charge and discharge cycles. Compared to measurements of resistance or impedance, EIS is able to present more complete results than those obtained when considering measurements at only one frequency, making it possible to perform detailed analyzes of the internal electrical characteristics of the cell, which allows studying its behavior when a large number of processes occur interrelated and at different rates. It is important to emphasize the sensitivity of this measurement process, as mentioned in [11]. For this reason, the measurement tends to be influenced by a series of parameters associated with the adopted method, such as temperature, the cell's SoC, the stipulated resting time after the SoC is defined, the setup adopted for the measurement, among others.

Due to the high dimensionality of the EIS spectrum obtained from measurements with the BT4560 equipment (Hioki) - since the measurements are constituted by a real and an imaginary portion of the impedance in a frequency range that extends between 0.1 Hz to 1.05 kHz – it is a challenge to identify quantitative characteristics that can be correlated with individual cell degradation.

One of the methodologies adopted to analyze the obtained data is the Nyquist diagram, in which the horizontal axis contains the resistance measurements and the vertical axis includes the reactance measurements. Figure 3 presents a graph containing the EIS measurements performed in cells with capacities equivalent to 98, 80, 75 and 66% of their nominal value - the highest frequencies are on the left of the graph.

The approaches commonly adopted for the analysis of these graphs tend to reduce the spectrum in lower dimensional characteristics: normally adjusting it in order to compose an equivalent circuit model. This type of adjustment can lead to uncertain conclusions and it is questionable whether a purely electrical model can capture the physical, chemical and material properties and processes of a battery - focusing only on individually chosen frequencies [12]. Due to these limitations, and in order to enable the beginning of the

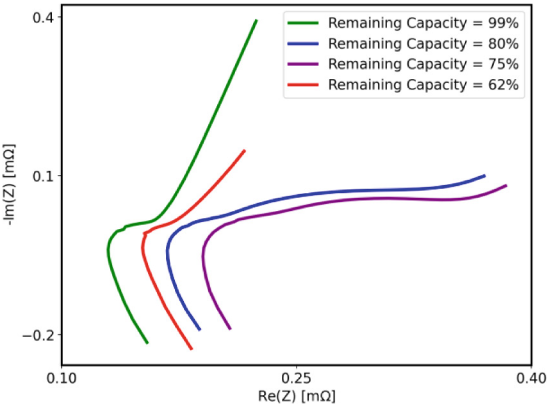

Fig. 4. EIS measurements of cells with different capacities

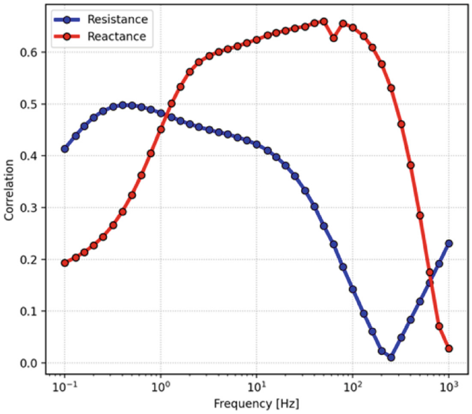

Fig. 5. Correlation between Re(f) x SoH (blue line) and X(f) x SoH (red line)

analyses, it was decided to develop specific algorithms for the analysis of the spectrum as a whole. To select the resistance and reactance values to be used, a graph comparing the correlation between Resistance and Reactance (which will be called Re(f) and X(f), respectively, where f is the measurement frequency) was generated.

The correlation values obtained according to the frequency are shown in Fig. 5. From the results, it was concluded that the most suitable input values for the constitution of a cell selection methodology based on computational methods were: (1) Resistance measured at the frequency of 0.4 Hz (Correlation of 0.5) and (2) Reactance when the frequency is 50 Hz (Correlation of 0.66). These frequencies can be related to the diffusion processes of lithium ions in solid particles.

Data-driven methods do not require prior knowledge of battery operation, relying solely on collected data. This is especially relevant considering that it is normally not possible to access the data collected by the BMS (Battery Management System) during the first battery life. Despite being recommended in regulations (UL 1974), in some cases, BMS data may not be available for analysis due to confidentiality criteria inherent to the development of commercial products. In this situation, a process for performing an in-depth analysis of incoming samples is necessary, including a procedure to determine the integrity of cells and other parts of the system by testing aged samples and comparing them with documentation and testing of new cells.

4 Cycling Tests

Prolonging the use of batteries being taken out of EVs in new applications is highly desirable, both for the automotive industry and the general public, as it will be possible to increase the residual value of EVs and potentially create new markets in energy storage applications, thus lowering the sales prices of EVs and these storage systems. When considering the environmental scope, there will be a reduction of chemical and metallic waste, along with the energy consumed to produce new batteries.

Energy storage systems are indispensable parts of different electrical systems, for applications such as the provision of ancillary services to the electrical grid, energy backup, storage associated with generation from renewable sources, micro grids, new vehicular applications (e.g., electric forklifts), among others, favorable to the use of second-life batteries from EVs. This could make investments in these systems more attractive and shorten the payback period.

In order to analyze the adaptability and aging behavior of batteries when considering the typical operating regimes of the main second-use applications, tests were carried out considering two scenarios: use in Stationary Application (IEC 62620) and on-grid Photovoltaic Application (IEC 61427 -2 – Time-Shift). These laboratory tests consist of the application of specific charge and discharge profiles under controlled temperature conditions. In most applications, it is impracticable to wait for a cell to age faithfully reproducing the normal conditions of its operation, so the tests seek accelerated aging, which can be carried out through uninterrupted cycling, the use of high currents and high temperatures.

The Durability Test (Cycles) is performed according to the procedure described in item 6.6.1 (endurance in cycles) of the IEC 62620 (2014) standard, entitled “Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary lithium cells and batteries for use in industrial applications”. Discharges were carried out at 0.5C with constant current of 0.5 x C1 until the cell reached the final discharge voltage of 2.0 V. Charges were carried out with voltage and current limited to 3.6 V and 135 A, being finalized after a period of 3.0 h. Following the guidelines of the standard, there is no rest between a charge and a discharge and every 100 discharge and charge cycles, a capacity test in Nominal Regime (C5) is carried out to evaluate the loss of capacity of each sample, according to the results shown in Fig. 6.

It is necessary to mention that the sample with 100% capacity (in dark red) that has shown a more abrupt degradation behavior than the other sample of similar capacity is performing its cycles at 35 °C, that is, 10 °C above all other cells. Thus, it was possible to identify the expressive impact of temperature on the useful life of these units.

The other durability test, based on cycling, is carried out according to the procedure described in item 6.5 (Test for endurance in photovoltaic energy storage, time-shift

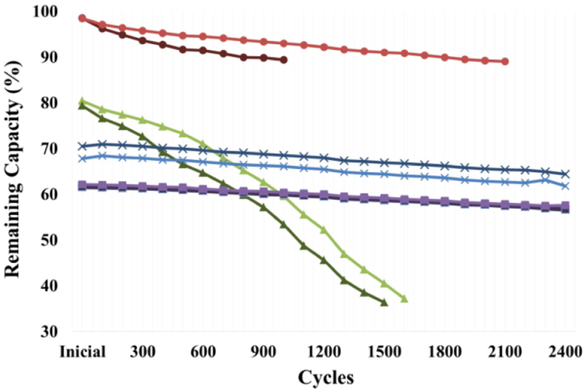

Fig. 6. Cycling performed according to the procedures described in IEC 62620

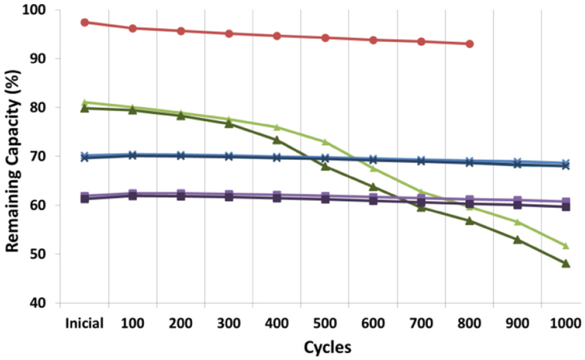

Fig. 7. Cycling performed according to the procedures described in IEC 61427–2

service) of the IEC 61427–2 (2015) standard, entitled "Secondary cells and batteries for renewable energy storage – General requirements and methods of test – Part 2: On-grid applications". The operating mode is the "photovoltaic energy storage time-shift duty", which aims to store the energy generated by the photovoltaic system at times of surplus generation and inject the stored energy into the electricity grid at times of high demand, resulting in more appropriate use of photovoltaic energy.

Discharges were carried out at 0.5C, with constant current of 0.5 x C1 until the cell reached the final discharge voltage of 2.0 V. Charges were carried out with voltage and current limited to 3.6 V and 135 A, being finalized after a period of 3.0 h. It is important to mention that the procedure described in IEC 61427–2 establishes that at the end of the discharge, the cell must not be charged again until reaching the duration of a complete cycle of 24 h. In this context, it was decided to decrease the resting time to cause a more accelerated aging in order to evaluate the degradation of cells in this cycling profile. Every 100 discharge and recharge cycles, a capacity test in Nominal Regime (C5) is carried out to evaluate the loss of capacity of each sample, which allows the generation of the graph represented in Fig. 7.

The analysis of the graphs described in Figs. 6 and 7 allows the conclusion that new cells, with higher remaining capacities, showed a more abrupt decay in capacity when considering this cycling context than aged cells, which did not present significant rates of aging during the tests. On the other hand, cells with 80% SoH show a tendency to age faster than the others, even compared to those that initially had lower remaining capacity. It is possible to conclude that there are possible internal effects of cell degradation causing this unexpected behavior, that is, the determination of the remaining capacity by itself may not be a sufficient parameter to determine the remaining useful life of these units - highlighting the need to carry out complementary studies. It is possible that all these cells come from the same battery, which probably faced more severe operating conditions (such as high temperatures, an accident or flood) during its first life - which may even justify the reason they were removed from the vehicle still with high capacity.

5 Energy Storage System Development

Given the growing market for EVs, reusing/repurposing their batteries could represent a low-cost energy storage market for utilities, electricity consumers and other stakeholders. This is a promising strategy that can help to reduce the initial costs of batteries. Within the scope of this project, the focus is the development of an energy storage system (rated voltage of 48 Vdc) composed of second-life cells, which will be destined for applications associated with on-grid photovoltaic systems at the residential level.

Energy storage systems composed of second-life batteries can be used in stationary and mobile applications, being possible to reuse them completely or dismantle them at the module or cell level for the configuration of new products. In order to allow for a more in-depth analysis and the development of a customized energy storage solution, it was decided to dismantle the modules received at the cell level – allowing them to be grouped according to their remaining capacity in new custom configurations. This process is the alternative with the highest final cost given the need for disassembly and repackaging procedures and new BMS development. From an economic and technical point of view, if there is the possibility of reusing the entire battery without disassembling it, this should be the preferred option [13].

5.1 BMS and Algorithms Development

Fundamental components in new generations of batteries are electronic management and control systems, called BMS. These systems play a fundamental role in the safety and performance of batteries - for example, the lithium-ion battery uses an electrolyte that is stable only within a certain voltage range, as it decomposes outside this range, which can lead to the battery exploding or catching fire.. Among the various functions that a BMS has, the main one is the load balancing of the battery cells. In addition to this task, others are performed, such as measuring the voltage, current and temperature of the system, the SoC and SoH of the cells and, based on these variables, even the determination of the RUL. Specifically, from the data collected from each cell, the system may be able to calculate or estimate certain parameters related to the state of the battery cells, providing useful data to the system:

a) The SoC quantifies the available charge at each instant of time and provides an indication of the remaining battery autonomy;
b) The SoH quantifies cell degradation and allows assessing whether the battery is still capable of meeting the application's energy and power specifications;
c) The balancing algorithm is responsible for transferring the load of cells considered unbalanced in order to equalize its SoC through hardware elements.

Using estimates to predict cell behavior is another trend. While the SOH determines the degradation of the cell at the current instant and can provide information on the amount of energy and power the cell is capable of delivering at that instant, the use of information to predict the degradation in future instants and determine the time remaining until the EoL is one of the most recent subjects in this field. RUL is the name given to these estimators, which enable, for example, the predictive maintenance of a set of batteries or the intelligent management of charge and discharge.

The motivation for developing these algorithms stems from the fact that the projection of remaining useful life of lithium-ion batteries can be distorted due to complex chemical reactions that occur inside the battery cells during the charging and discharging processes. Approaches cited in the literature are classified into two categories: (1) experience-based methods that consist of accumulating experience during system operation, in addition to requiring a large amount of data for model development; (2) performance-based methods make their predictions indirectly, using some LiB measurements as a subsidy.

Performance-based methods can be subdivided into two categories: (a) data-based methods are machine learning techniques that use a large amount of data to perform the training and validation of these algorithms. (b) model-based methods use a system identification technique associated with a model capable of reproducing cell behavior. In the developed algorithm, it was decided to use a model-based technique called Unscented Kalman Filter (UKF) and associated with a generic model capable of reproducing the behavior of the battery aging curve. The UKF filter is responsible for providing adaptability to the algorithm, as only the generic model is not capable of following the dynamic behavior of the battery [14]. Initially, the algorithm checks the battery's SoH and configures the initial states of the filter based on a mapping of the model parameters. This mapping was performed based on the aging curves extracted through the cycling tests. After this step the UKF estimates the parameters of the generic model in every iteration, which serve as a subsidy for carrying out aging projections. Based on these estimated parameters, the algorithm projects the aging behavior of a battery up to the end of its useful life cycle by cycle for a given application.

Figure 8 shows the process used by the algorithm to estimate the remaining battery life. Calculations are performed based on the current SoH and knowledge gained over the course of battery operation. After running the EoL estimates, Fuzzy Logic is used to evaluate these estimates and remove large variations on the remaining life projections that naturally occur in Li-ion batteries. Thus, the invention in question removes these distortions before presenting the information to the user.

From the EoL estimates and the current battery cycle, Fuzzy Logic performs the fuzzyfication process that consists of determining the degrees of relevance of the inputs in relation to the Fuzzy set. The rule base is used by the algorithm as evaluation criteria

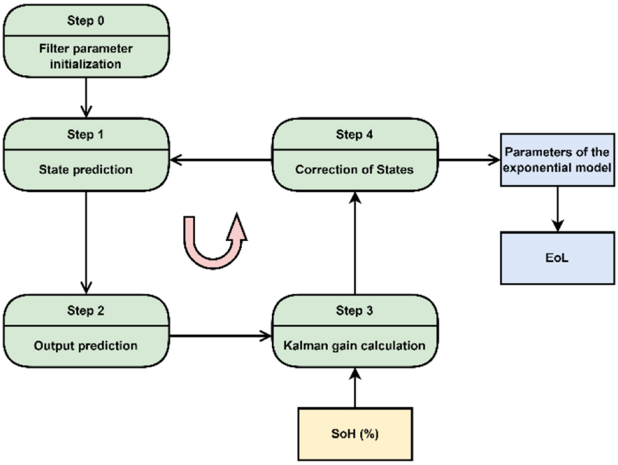

Fig. 8. Remaining useful life estimation process

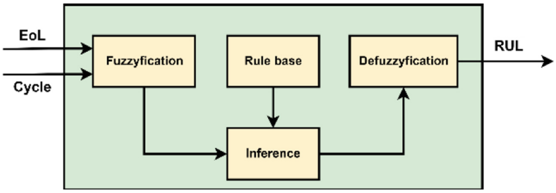

Fig. 9. Fuzzy inference process.

to perform its inferences and this result is defuzzyfication. This process consists of the decision making by the algorithm, which selects the best value based on existing inferences [15]. The algorithm performs decision making using the centroid strategy, in which estimates are balanced with the weights obtained in the inference process. The result of this whole process is the battery RUL as shown in Fig. 9.

6 Final Considerations

When reaching the end of their useful life in electric vehicles, batteries still have about 80% of their available capacity, allowing them to be reused in other types of application in which operating conditions are less severe. This reuse opportunity generates new possibilities for the market, allowing for the creation of new business models. Another factor to consider when choosing to use second-life batteries, is that not all EV battery cells degrade in exactly the same way for a variety of reasons, including temperature gradients within the battery and minor manufacturing differences.

This means that the performance of second-life batteries can be potentially unpredictable. In other words, when they are removed from their first application and sent to the reconditioning/reuse centers, there is not much information about these batteries. One possibility for obtaining this information is the analysis of the data stored in the

BMS, however, they are not always available. Thus, it is necessary to submit the battery to a series of procedures in order to enable the analysis of its health status and determine if it is really suitable for a new use. The test procedure may include open circuit voltage measurements, internal resistance determination, capacity tests, self-discharge tests, among others. During the execution of the project described in this article, it was decided to use EIS measurements, highly correlated with the remaining capacity of received second-life cells, for the composition of a rapid methodology for cell selection.

In a complementary way, the cycling tests are still in progress, which are of paramount importance for the project, as it aims to provide data for the analysis of the behavior of the cells when subjected to different operating regimes similar to those used in real conditions of use. In this regime, the cells have shown a very satisfactory degradation behavior, not showing a loss of expressive capacity during cycling..

The development of an energy storage solution from degraded cells during application in EVs previously used in the country will strengthen the technological advancement of the national EV and battery industry. In addition, this project is fully aligned with the concept of circular economy, providing the reuse of elements that would initially be discarded or sent for recycling.

Acknowledgments. We would like to thank CPFL Energia, ANEEL and the R&D project ANEEL CPFL PD-00063–3061/2019 CS3061 for enabling studies on such an important and innovative topic for the electrical and automotive sector, in addition to society and the environment as a whole.

Authors' Contributions. The authors confirm contribution to the paper as follows: Aghatta Moreira was responsible for the initial draft of the article; Maria de Fatima Rosolem, Raul Beck and Vitor Arioli performed the study conception and design; Thiago Nascimento, Fernando Padela and Gustavo Contin were responsible for data collection and hardware developments; Aghatta Moreira and Marcelo Camboim are involved in the analysis and interpretation of results; Jonathan Moura, Marcelo Camboim and Thomas Nunes are involved in the development of the SoC, SoH and RUL algorithms; Vitor Arioli, Camila Omae and Hongwu Ding reviewed the article critically for important intellectual content and were involved in project development management processes. All authors reviewed the results and approved the final version of the manuscript.

References

1. International Energy Agency (IEA). Tracking Transport 2020. Available at: https://www.iea.org/reports/tracking-transport-2020. Accessed August 2022.
2. International Energy Agency (IEA). Global EV Outlook 2021: accelerating ambitions despite the pandemic. Available at: https://iea.blob.core.windows.net/assets/ed5f4484-f556-4110-8c5c-4ede8bcba637/GlobalEVOutlook2021.pdf. Accessed August 2022.
3. M. Dennis, "Are We on the Brink of an Electric Vehicle Boom? Only with More Action". World Resources Institute. September, 2021. Available at: https://www.wri.org/insights/what-projected-growth-electric-vehicles-adoption. Accessed August 2022.
4. Richa K, et al. A future perspective on lithium-ion battery waste flows from electric vehicles. Resour Conserv Recycl 2014;83:63e76. Feb.

5. Hossain E, et al. A comprehensive review on second-life batteries: current state, manufacturing considerations, applications, impacts, barriers potential solutions, business strategies, and policies. IEEE Access 2019;7:73215e52. Institute of Electrical and Electronics Engineers Inc.
6. H. Man. “What are LFP, NMC, NCA batteries in electric cars?”. Zecar. August 2022. Available at: https://zecar.com/post/what-are-lfp-nmc-nca-batteries-in-electric-cars. Accessed August 2022.
7. Maharshi S, Janardhan Reddy K. Cloud based disassembly of electric vehicle battery. Procedia manufacturing, vol. 30; 2019. p. 136e42. Jan.
8. Thompson, a. Economic implications of lithium ion battery degradation for vehicle-to-grid (V2X) services. In: Journal of Power Sources, v. 396, 2018.
9. Christopherson, Jon. Battery Test Manual For Electric Vehicles. Idaho National Laboratory, 2015.
10. Carvalho, Liliane A. De; Andrade, Adalgisa R. de; Bueno, Paulo R. Espectroscopia de impedância eletroquímica aplicada ao estudo das reações heterogêneas em ânodos dimensionalmente estáveis. Química Nova, v. 29, n. 4, p. 796–804, 2006.
11. Andre, D. et al. Characterization of high-power lithium-ion batteries by electrochemical impedance spectroscopy. I. Experimental investigation. Journal of Power Sources, v. 196, n. 12, p. 5334–5341, 2011.
12. Zhang, Yunwei et al. Identifying degradation patterns of lithium ion batteries from impedance spectroscopy using machine learning. Nature communications, v. 11, n. 1, p. 1–6, 2020.
13. Ahmadi, L., Yip, A., Fowler, M., Young, S.B., Fraser, R., “Environmental feasibility of re-use of electric vehicle batteries”, Sustainable Energy Technologies and Assessments 6:64–74, 2014.
14. Duan, B., Zhang, Q., Geng, F., & Zhang, C. (2020). Remaining useful life prediction of lithium-ion battery based on extended Kalman particle filter. International Journal of Energy Research, 44(3), 1724-1734
15. Zadeh, L.A. Fuzzy sets. Information and Control, v. 8, n. 3, 1965