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Published in:
Energies

DOI (link to publication from Publisher):
https://doi.org/10.3390/en16052345

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Nováková, K., Prazanova, A., Stroe, D-I., & Knap, V. (2023). Second-Life of Lithium-Ion Batteries from Electric Vehicles: Concept, Aging, Testing, and Applications. *Energies*, *16*(5), 1-20. [2345]. https://doi.org/10.3390/en16052345

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energies

Perspective

Second-Life of Lithium-Ion Batteries from Electric Vehicles: Concept, Aging, Testing, and Applications

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Abstract: The last decade has seen a significant increase in electromobility. With this trend, it will be necessary to start dealing with the subsequent recycling and disposal of electric vehicles, including the batteries. Currently, the battery is one of the most expensive components of an electric vehicle, which in part hinders their sufficient competitiveness with the internal combustion engine. Furthermore, the lifetime of a battery for use in an electric vehicle is assumed to be 8–10 years/160,000 km, after which the battery capacity drops to 80% of the initial capacity. However, it transpires that a battery at the end of its life in an electric vehicle does not need to be disposed of immediately, but can be used in other applications wherein the emphasis is not so strictly on an excellent power and capacity capability related to its volume or weight. Thus, reusing batteries can help reduce their cost for use in electric vehicles, increase their utility value, and reduce the environmental impact of batteries. This paper discusses methods for researching battery aging in electric vehicles, testing methods for batteries during the transition from first life to second life, and prospective battery second-life use and its specifics. The main contribution of this perspective article is to provide a comprehensive view of the current state of second-life batteries and an overview of the challenges that need to be overcome in order to use them on a large industrial scale.

Keywords: lithium-ion batteries; second-life; incremental capacity analysis; electric vehicles

Citation: Nováková, K.; Pražanová, A.; Stroe, D.-I.; Knap, V. Second-Life of Lithium-Ion Batteries from Electric Vehicles: Concept, Aging, Testing, and Applications. *Energies* **2023**, *16*, 2345. https://doi.org/10.3390/en16052345

Academic Editors: Desmond Gibson, Mojtaba Mirzaeian, Peter Hall and Saule Aidarova

Received: 31 January 2023
Revised: 19 February 2023
Accepted: 21 February 2023
Published: 28 February 2023

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1. Introduction

Over the past few years, the entire energy sector has been transformed on a massive scale. This transformation is due to both conventional energy sources' natural end of life and the European Union's initiative to achieve carbon neutrality by 2050 [1]. With the decommissioning of fossil-fuel-based conventional power plants, it will be necessary to find other ways to guarantee the stability of the grid, as the power delivered by renewables is weather-dependent. Combining them with battery storage is one way to appropriately complement photovoltaic (PV) and wind power plants and achieve stable output. Today, most battery storage systems are assembled from new battery modules customized to the specific application. The clear advantage of this approach is the best possible battery performance and long lifetime. Still, the significant disadvantage is the initial purchase price. Therefore, various ways of reducing battery price are being sought.

At the same time, electric vehicles (EVs) are on rise due to their local environmental friendliness and legislative incentives. However, their market adoption at a large scale is hindered by the high cost of batteries. Thus, a concept that could address both needs concurrently is the second-life use of lithium-ion batteries. A traditional milestone in the life of an EV battery is currently a capacity fade of 20–30%, when the battery can no longer meet the requirements of a traction battery [2]. However, end-of-life (EOL) EV batteries do not need to be disposed of immediately, as they retain enough performance (in terms of both capacity and power) and can be used in less demanding applications such as battery energy storage systems. Consequently, selling used EV batteries would compensate for the high purchase cost of EVs, and would enable a lower-cost solution for stationary energy storage systems.

At present, there are relatively few second-life battery (SLB) demonstrators available, and therefore there is no particularly serious pressure on the industrial sector to address their application. However, this situation is likely to change in the near future. From 2016 to 2021, the number of EVs sold has increased sevenfold from 500,000 EVs to 3,500,000 EVs sold per year [3]; furthermore, this growth is expected to continue. As the lifetime of EV traction batteries is designed to be 8–10 years/160,000 km, it is clear that with this delay, the same increase can be expected in SLB, for which a use needs to be found [2–4].

Since an SLB is not a product with clearly defined parameters like a new battery, it is necessary to determine, as correctly as possible, the state-of-health (SOH) of the battery after its retirement from the EV. Thus, testing and sorting the batteries at the transition point from first life to second life is crucial. If the grouping of batteries for further use is not carried out correctly, the whole SLB system will be poorly balanced, and the optimum desired performance cannot be achieved. For this reason, rapid degradation of the assembled SLB system will occur. In the worst-case scenario, if the grouping of the batteries for further use is incorrect, the battery management system (BMS) may fail due to the overloading of the balancers and overheating. On the other hand, sensitive sorting can significantly extend the life of second-life battery technologies. The possible life cycle of a battery with second-life use is shown in Figure 1.

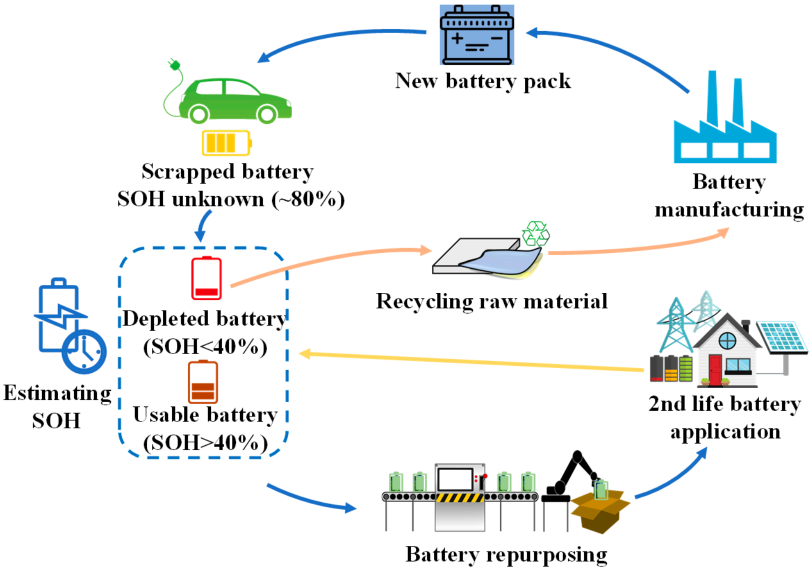


Figure 1. The life cycle of a battery with second-life use.

In principle, R&D projects focusing on second life can be divided into two directions: scientific and industrial projects. Scientific research and academic projects focus on describing a battery's life cycle as accurately as possible. By comparing the huge dataset collected and the measurement results of one particular battery, it should be possible to figure out the current state of the battery under investigation.

The behavior of second-life batteries is mainly dependent on their use during their first life. Currently, the most commonly investigated factors affecting battery degradation in EVs are their operating temperature [2], the driving habits of the driver [5], the depth of battery discharge [6,7] and the number of cycles [8], or a combination of these parameters [9].

At the end of the battery's first life, the battery is tested for its condition using several methods. The most widely used are capacity tests and internal resistance tests (using the DC pulse technique) [8], which are the simplest but also the most time-consuming.

Nevertheless, they are currently the most widely used methods, including in academia [4]. For a more comprehensive assessment of battery degradation, electrochemical impedance spectroscopy (EIS) or incremental capacity analysis (ICA) [10–12] methods are used.

Finally, the use of batteries in their second life needs to be evaluated appropriately. For example, batteries can be used for various ancillary services, peak shaving and backup power sources, or as a suitable complement to fast EV chargers to increase the possible power provided [13–15].

As demand for the characterization of batteries is high, there is currently a great effort underway to characterize batteries and their degradation processes by simulations [11]. As helpful as this method can be in understanding the entire battery life cycle properly, it should only be used as a complement to experimental measurements. However, especially in the case of extrapolation, it may be that the simulated data will not correspond to the actual situation. If these data are used in the design of the actual battery storage system, the actual lifetime may be much lower than predicted, and in extreme cases, failure may occur.

The main contribution of this article is to summarize the most recent developments of second-life batteries and to offer a perspective on the challenges encountered by this technology. The article focuses both on the pitfalls at the point of transition of a battery from an EV to a second-life application, and on the challenges of using second-life storage. Therefore, in this study, sufficient space is devoted to evaluating the economic side of the issue, which appropriately complements the description of the situation from the technical side.

The paper is structured as follows. Aspects of battery aging toward second life, focusing on laboratory testing and simulations, are described in Section 2. Section 3 is focused on battery characterization and sorting at the beginning of the second life, covering various tests and future needs. Application and demonstrator projects are introduced in Section 4. Section 5 is then dedicated to economic and environmental perspectives. Finally, a summary and discussion are provided in Section 6.

2. Battery Ageing in the Context of Second-Life Batteries

It is well known that the type of load profile heavily impacts Li-ion battery aging and thus its lifetime [9]. The challenge is then grouping batteries with the same SOH (as that might be unknown) and with the same history, as the batteries' future aging depends on it. Since there are currently no experimentally measured data over the entire lifetime of an EV that can be paired with the results from measurements at the beginning of the second life, researchers are investigating different approaches to obtain these data. While classical methods in which cells and modules are experimentally aged in climate chambers are a suitable choice in terms of accuracy, the time required to obtain results and the economic costs of these methods are clear disadvantages. For these reasons, it is reasonable to use simulation models to study general battery degradation, as it is caused by different aging mechanisms (e.g., solid electrolyte interface growth, lithium plating, electrode cracking, etc.) and their possible interactions [16].

2.1. Aging in Climatic Chamber Based on Driving Profile

The conventional method for determining the aging behavior of batteries in an EV is by performing accelerated aging of cells and modules in climate chambers. Traditionally, the battery calendar and cycle degradation behavior are evaluated based on extensive test matrices which consider the effect of various stress factors (e.g., temperature, C-rate, etc.) and their levels [17–19]; during the tests, the stresses (and their levels) are changed one-by-one, and their effect on the battery performance degradation is monitored. However, incorporating the full test matrices is often too expensive, and often they are diminished by the use of standardized driving profiles (e.g., WLTP—Worldwide Harmonised Light Vehicles Test Procedure) instead of a detailed current dependence [16]. In the case of using a driving profile, human and environmental factors such as main use, climate, driving style, topography, and recharging routines can be considered [6].

An example of EV battery testing based on the WLTP profile is presented in Figure 2. Firstly, the battery is charged using the constant current–constant voltage (CC-CV) method. Then, the WLTP driving cycle is applied to the battery to emulate the EV driving; to emulate different EV trip lengths, the WLTP driving cycle can be applied consecutively, resulting in different depth of discharge cycles to the battery, as presented in Figure 2. Similarly, the effect of different EV charging strategies can be studied, while EV driving is still emulated with the WLTP driving cycles, as illustrated in Figure 3. These tests are continuously repeated to simulate the battery aging. At predefined time intervals, reference performance tests are carried out to measure the battery degradation in terms of capacity fade and/or internal resistance increase [20].

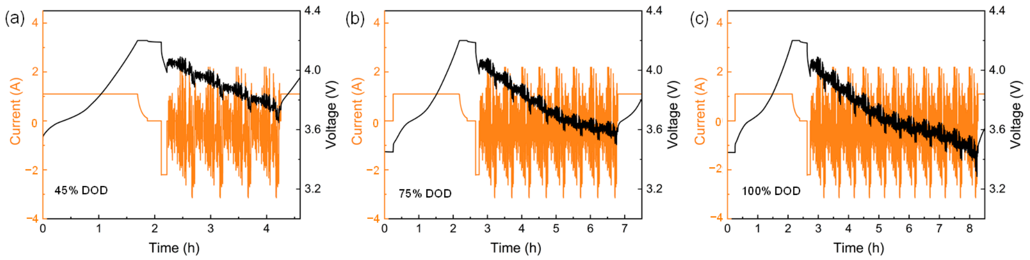


Figure 2. Battery testing using CC-CV charging and the WLTP driving cycle for discharging to investigate the effect of the cycle depth on battery degradation; (**a**) four WLTP cycles are applied to discharge the battery to 55% SOC; (**b**) eight WLTP cycles are applied to discharge the battery to 25% SOC; (**c**) 11 WLTP cycles are applied to fully discharge the battery.

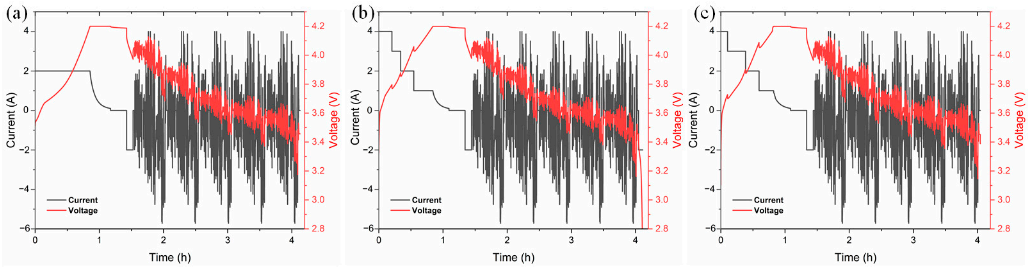


Figure 3. Battery testing using different charging strategies for charging and the WLTP driving cycle for discharging to investigate the effect of multi-step charging strategies on battery degradation; (**a**) CC-CV charging and five WLTP cycles applied for discharging; (**b**) multi-step CC-CV charging (MCCCV1) charging and five WLTP cycles applied for discharging; (**c**) MCCCV2 charging and five WLTP cycles applied for discharging.

Nevertheless, the aging studies which use driving profiles and are presented in the literature present one of the following limitations. The first one is applying the WLTP driving cycle to regular Li-ion batteries which were not manufactured for EV applications. This is the case for example of the work presented in [21], where the authors have used the WLTP driving cycles to age NMC-based Li-ion batteries with a capacity of 3.4 Ah and a nominal voltage of 3.6 V; based on the obtained results, they then developed a simple and accurate SOH battery algorithm that should be transferable to larger batteries used in the automotive industry. The second one is testing batteries manufactured for EVs not by driving cycles but by using standard calendar ageing conditions, which may not necessarily reflect the idling conditions of batteries in EV applications. This approach was used by Stroe and Schaltz in [21], wherein 63 Ah LMO/NMC-based EV Li-ion batteries were aged for eleven months at different SOCs and at different temperatures; subsequently, the authors have used the ICA technique to develop a SOH estimation method for the tested EV batteries.

The aforementioned battery aging limitations were overcome in the work of Micari et al. [22], who use the WLTP CLASS 3B driving cycle method to test LMO-NMC cells with a capacity of 63 Ah for the automotive industry. These cells are aged at 25 °C for 4184 cycles, corresponding to 8 test years. Thus, this work perfectly summarizes the advantages of the previous two methods, and its results, which mainly include capacity decrease over time and IC curves, can be used as a robust collection of measured data for possible further follow-up research.

2.2. Software Simulations of Second-Life Batteries

The main advantage of analyzing battery aging based on simulation models is their unambiguously low instrument requirement. However, apart from detailed electrochemical modeling, another indisputable advantage worth mentioning is the time required to obtain the required data.

The most important way in which second-life batteries are simulated is the simulation of their use in various second-life applications. There are many scenarios in which second-life batteries (SLB) are used in second-life applications, and there is an associated large variability of scenarios for their further aging. For this reason, computer simulations are often used to predict the remaining battery life.

The outputs mentioned below are based on computer-simulated battery behavior in various applications. They demonstrate that it is possible to extract significant important information from the software model before putting the real circuitry into operation. For example, M. Alhadri et al. [23] investigated the use of SLBs from electric aircraft in residential homes in combination with photovoltaics, and they drew the following conclusions. Although LIBs retired from their first life in electric aircraft or vehicles can handle a higher discharge rate than charge rate, they can operate properly for their second life in the PV grid-tied battery system, which needs a higher charge rate than discharge rate. Retired LIBs generate 20% more heat during the charge and discharge processes than fresh LIBs. This makes it necessary to put more emphasis on their thermal management system compared to the new batteries. The LIB that is retired from an electric aircraft after about 2.5 years can operate for 10 more years in the PV grid-tied battery system if the criterion for the retirement of the LIB from the first life and the second life is a capacity fade of 15% and 50%, respectively [23].

In the laboratory, often only single cells are tested, although real applications consist of many cells connected in modules. The differences between the remaining second life of individual cells and whole modules can be found in the work of P.V.H. Seger et al. [24]. It is visible that the more cells that are associated in series, the narrower the range of the cycled capacity of the pack. This is due to the fact that with more and more cells in series, the probability of having a weak cell with a fast capacity loss tendency that will limit the entire pack is higher.

Another major sector in which SLBs could find their application is in grid stability services. The use of SLBs in combination with a gas turbine to provide area regulation services was discussed by L. Canals Casals and B. A. García [15]. In this work, using a simulation model, they show that the way SLBs are used will have a significant impact on their remaining lifetime, and therefore, this must be considered in the initial design. In fact, in a scenario with lower battery requirements, the second-life EV battery works correctly for 1880 equivalent full cycles. On the other hand, more demanding load requirements lower the battery lifespan to 1241 equivalent full cycles, with the battery degradation accelerated by 21%.

3. Battery Testing at the Start of Second Life

Battery packs in EVs consist of battery modules containing cells connected in series and/or parallel to achieve the required voltage and capacity. To suitably assemble a homogenous SLB pack, it is necessary to know the main parameters of each cell or module, particularly the capacity and internal resistance. If cells with significantly different parameters (i.e., heterogenous cells) are combined, the performance of SLB packs will decrease, leading to short lifetime [25] and in the worst case, catastrophic failure. At the same time, the cells will need to be balanced more frequently for proper functioning, and their energy and power density will be compromised. These disadvantages of heterogenic cell bundling are the reason for the need to sort the cells well at the beginning of the SLB pack in order to achieve the best performance and longest remaining life [26].

3.1. Appropriate Testing Methods

The most widely used testing methods to evaluate batteries' electrical performance behavior are capacity and internal resistance measurements. However, when only relying on these measurements, one cannot fully understand the battery degradation during its first life, and the causes behind this degradation. Therefore, ICA and EIS are becoming more common, especially in the scientific community, as they can offer insights into battery degradation mechanisms and degradation modes [27]. All these methods, including their specifics, are described in the following subsections.

3.1.1. Capacity Test

The capacity test is the most common electrical characterization method for Li-ion batteries. It uses constant current (CC) or constant current–constant voltage (CC-CV) charging and discharging to obtain information about the battery capacity, energy, efficiency, and voltage curves [27]. Since these quantities are influenced by conditions such as temperature and C-rate, it is desirable to perform it within the selected reference conditions every time. As the battery ages, the maximum usable capacity of the battery decreases, as illustrated in Figure 4. The benefit of this method is that it directly provides the battery capacity, which is the most important performance parameter. However, this method is time-consuming, especially at low C-rates, and does not directly provide information about the battery history (i.e., how the battery was aged).

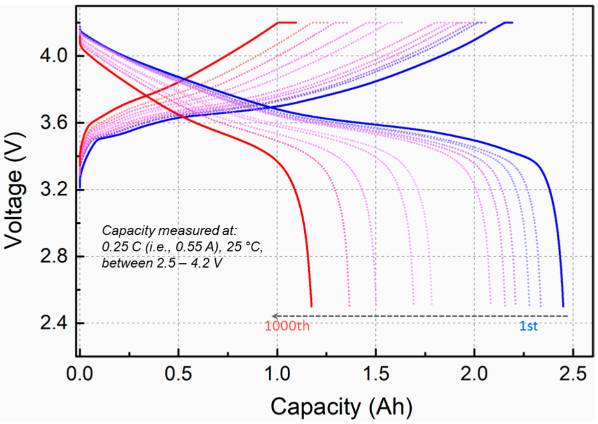


Figure 4. Evolution of the charging and discharging capacity voltage characteristic of a Li-ion battery during 1000 cycles; adapted from [28].

SLBs are characterized by a large variance in the capacity of individual cells. This is exemplified in [29] [], where the capacity of three cells from the same Nissan Leaf EV pack, were measured, returning values of 86.36%, 82.57%, and 74.92% from the one at the BOL. The measurement results of individual cells from one battery pack are shown in the in Figure 5. Thus, this method is suitable for basic coarse cell sorting.

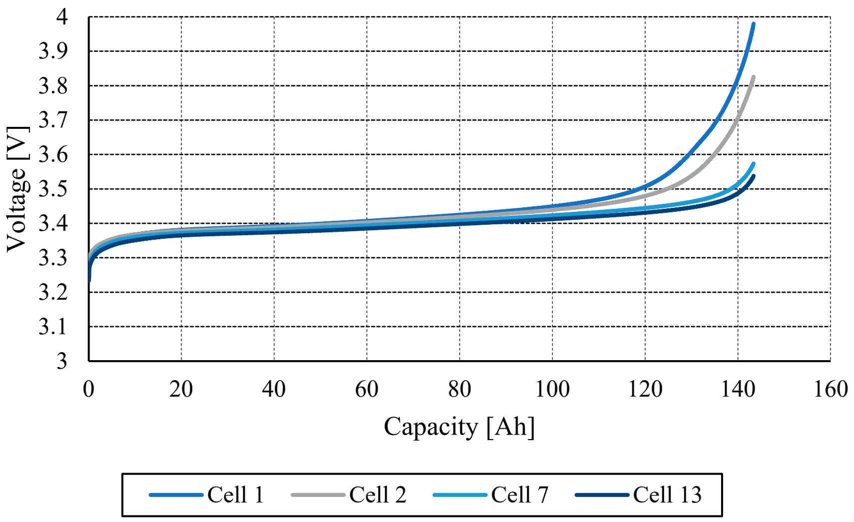


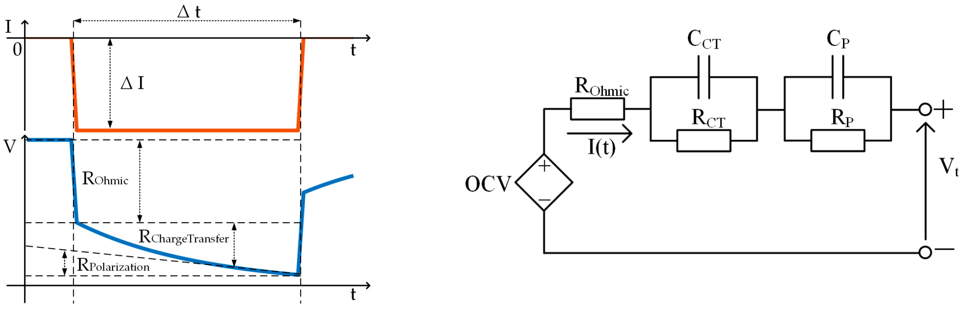
Figure 5. Example of four cells from the same battery pack of a total of 14 cells; adapted from [30].

3.1.2. Internal Resistance

Internal resistance can be considered the second most important parameter of Li-ion battery electric performance, as it is directly linked to their power capability. Since Li-ion batteries are a complex electrochemical system, the resistance is the effect of various internal electrochemical processes; typically, it is split into ohmic, charge transfer, and polarization resistance parts, which are results of electrochemical mechanisms and influence dynamic voltage response, as illustrated in Figure 6a. The internal resistance is generally measured via a current pulse that can be combined into a set of such pulses with different C-rates and lengths. One example of such a procedure is hybrid pulse power characterization (HPPC) or the pulse train [31]. The resistance can be then computed directly via Ohm's law:

$$R_{tx} = \frac{V_{t0}-V_{tx}}{I_{tx}-I_{t0}}, \tag{1}$$

where $t0$ is time right before the pulse is applied, and tx is the selected lasting of the pulse. R, V, and I, are resistance, voltage, and current, respectively. In this case, it is important to specify pulse length and the time coordinate for the resistance calculation, as it is dependent on time. Alternatively, the current and voltage signals during the pulse can be used for parameter identification of an equivalent electrical circuit model, as the one illustrated in Figure 2b. Then, the contributions of ohmic, charge transfer, and polarization resistance can be quantified.



(**a**) (**b**)

Figure 6. (**a**) Schematic illustration of a squared current pulse and indicated contributions of various resistance parts. (**b**) Equivalent electrical circuit model that can be used via parameter identification for a general quantification of the resistances.

Internal resistance measurement as a method for grading second-life batteries is used by Zhou et al., who tested 54 cylindrical 18,650 lithium-ion second-life batteries [32]. The pulse test is used by Zhou et al. as an effective method for evaluating battery consistency. As shown in Figure 7, the variation of the internal resistance values is not negligible and thus can be a significant parameter used in battery sorting at the beginning of the second life.

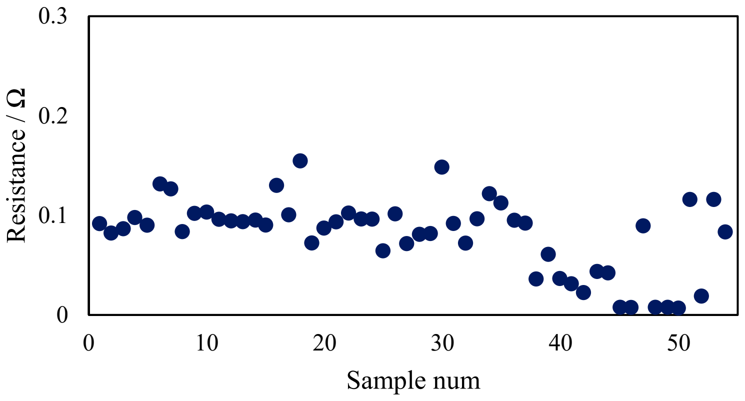


Figure 7. Resistance values of 54 s-life batteries [32].

3.1.3. Incremental Capacity Analysis

Incremental capacity analysis (ICA) is a method based on CC (dis)charging suitable for a detailed description of electrochemical processes inside a cell. Using ICA, the lithium intercalation and deintercalation processes and the corresponding staging phenomenon can be analyzed. In addition to this application, IC peaks and valleys can be used for determining and quantifying the battery degradation modes (LAM/LLI). The ICA technique consists of differentiating the battery charging capacity against the battery voltage. The voltage plateaus from the voltage–capacity curve are transformed into clearly visible dQ/dV peaks, illustrated in Figure 8, which are referred to as IC peaks. The amplitude of these peaks and their position in reference to the voltage axis determines the degradation state of the battery.

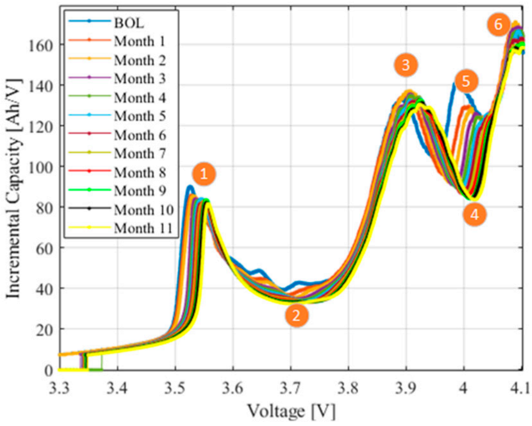


Figure 8. Evolution of the ICA curve during calendar aging of an NMC-based Li-ion battery with numbered peak and valley zones (adapted from [21]).

For correct method results, it is necessary to charge the battery at the lowest possible current because a high current strongly influences the reactions in the cells and leads to distortion of the IC peaks. At the same time, measurements must always be performed with the same constant current and at the same ambient temperature, otherwise the peaks and valleys cannot be tracked accurately, as illustrated in [21],[33].

The use of this method to estimate the condition of second-life batteries is discussed in the work of Braco et al. [34]. They concluded that this method is only suitable for the lower stages of degradation as it has limited accuracy, especially in the advanced stages of degradation. This is because for SOH values lower than 47%, it is not possible to identify any peak or valley with the C-rate used during the reference performance test (RPT) capacity measurement.

3.1.4. Electrochemical Impedance Spectroscopy

Electrochemical impedance spectroscopy (EIS) is a non-destructive method that characterizes electrochemical processes inside the battery. It can be used both for dynamic in situ measurements during battery cycling and for ex situ measurements in different states of charge and discharge. During EIS measurements, a small AC signal over a wide frequency range is applied to the battery, and the cell response is measured. Different components and processes within a cell operate on different timescales. Therefore, they have different time constants and can be separated in the frequency domain using this method. The measurements in the form of Nyquist plots and an illustration of its change during aging are shown in Figure 9 [35].

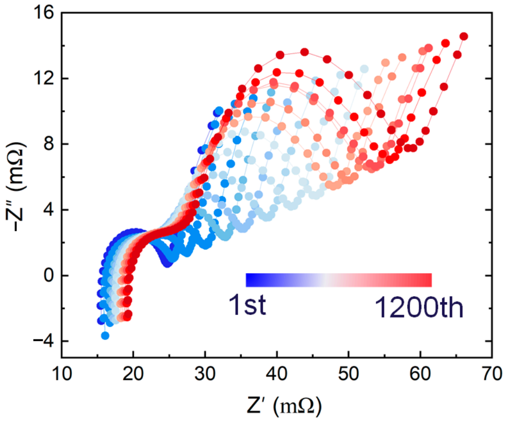


Figure 9. Evolution of the Nyquist plot (obtained through EIS measurements) due to aging from BOL to 1200 EFCs of an NMC-based Li-ion battery. Aging: WLTC discharging to 75% DOD and full re-charging with 0.5 C-rate at 45 °C. EIS measurement: 6.5 kHz–10 mHz frequency range, 50% SOC, and 25 °C.

Measurements of SLBs using this method have been carried out and published by E. Locorotondo et al. who show the results of impedance spectroscopy of 20 Ah lithium NMC batteries after EOL, precisely at 100, 85, 80, 60 and 50% of rated capacity, over a wide range of frequencies from 450 mHz to 3.5 kHz [36].

The measured waveforms vary depending on the SOH of the battery, but also on the SOC. For this reason, it is necessary to perform all measurements at the same SOC. The results from measurements performed by D. Kehl et al. [37] battery at 30% SOC and different SOH are shown in Figure 10. Module 4 has the lowest capacity of them.

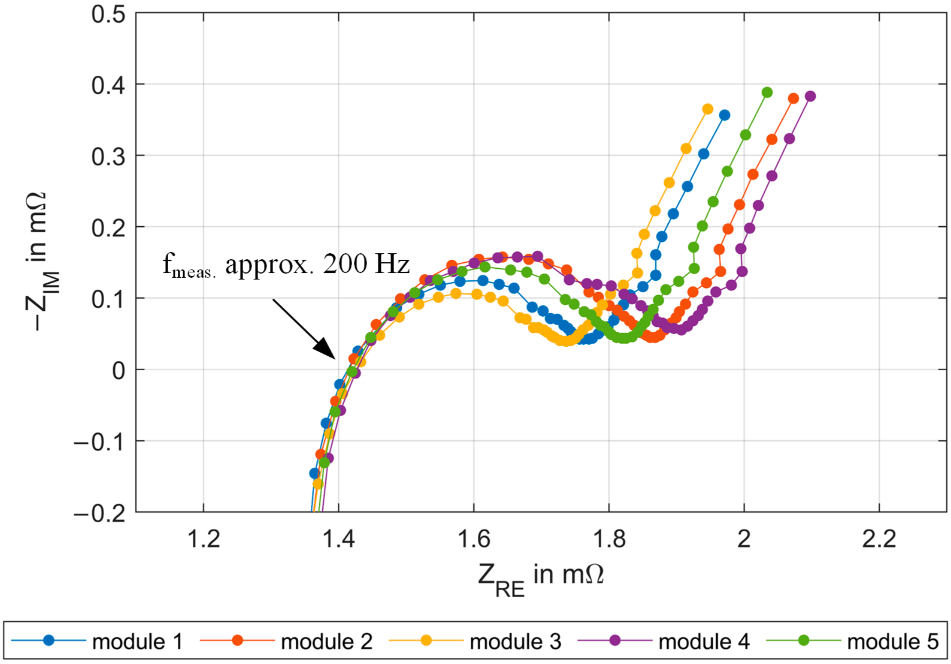


Figure 10. Battery impedance spectra of an NMC-based Li-ion battery at various SOH levels and 30% SOC (adapted from [37], licensed under CC BY 4.0).

3.2. Testing Requirements for SLBs

There are two main areas which need attention regarding SLBs testing. The first is the degradation evolution in the second-life stage depending on the first-life history; this has not been described in detail. Typically, there are only uniform conditions of first life considered in the literature, and these do not cover the possible mixture of a degradation mechanism entering the second life. Thus, a structured study is required to describe possible degradation trajectories, including their markers, at the beginning of the second life. These markers will be useful in the current situation which lacks battery passports that document the batteries' history and their current state.

Subsequently, the second area requiring attention is battery testing for their sorting by SLB storage manufacturers. They are required to screen the cells or modules to dispose of the unusable ones and to match the rest for the best performance of the storage system. Thus, the requirements for battery testing are high information value output, short testing time, and low investment and usage cost. In this regard, the capacity test, together with the ICA, can appear to be expensive in both energy and time. The internal resistance test requires unified SOC conditions and can carry only a limited amount of information due to different degradation histories. The EIS measurements have typically a high investment cost; they last significantly longer than a simple internal resistance test and they are bound to the same SOC conditions. Consequently, there is an opportunity to combine these methods and to optimize them in order to reduce their testing times and to complement the obtained information. This can lead, for example, to the utilization of a reduced charging interval used for capacity/ICA testing [38], followed by a set of pulses, such as direct-synthesis-ternary sequence [39], providing EIS-like information in a fraction of the time and without such high demand on hardware. Moreover, the aforementioned markers from the study investigating the effects of first-life history on second-life use can be utilized via machine learning to effectively sort and predict the lifetime trajectories of the tested SLBs.

4. Current and Future Applications of Lithium-Ion Second-Life Batteries

Several business scenarios were identified for using SLBs after the end of their first-life in EVs. Reports from the Electric Power Research Institute indicate that the most economically attractive stationary second-life applications include transmission (TD) and time of use (ToU), deferral (benefits coming from investment deferral), area regulation, and support to renewable energy generation [40]. When charging EVs, the standard state of the distribution network is disrupted by power peaks above the expected demand, so it is appropriate to use SLBs also as a support for fast charging stations for EVs [14]. In the context of off-grid systems, SLBs can be used to provide electricity when consumption is not covered by wind and/or photovoltaic sources by themselves [13]. The following subsections discuss the specifics of each SLB's application.

4.1. Residential Microgrids

Electrical devices for space and water heating generate the majority of electricity consumption in households. However, the power consumption varies during the day. Suppose a renewable energy source is integrated into the residential grid. In that case, it is possible to achieve partial self-sufficiency, but in most cases, there is no overlap between the maximum power produced and the maximum power consumed. For this reason, battery storage systems are installed together with domestic PV plants so that the energy produced during the day can be used later. However, battery storage is the part that significantly increases the installation cost, and by using SLB, the purchase cost can be significantly reduced. A possible scenario of using SLB in combination with PV panels is shown in Figure 11. The use of SLB batteries (retired from Nissan Leaf EVs) in a microgrid application was studied from an aging perspective in [40].

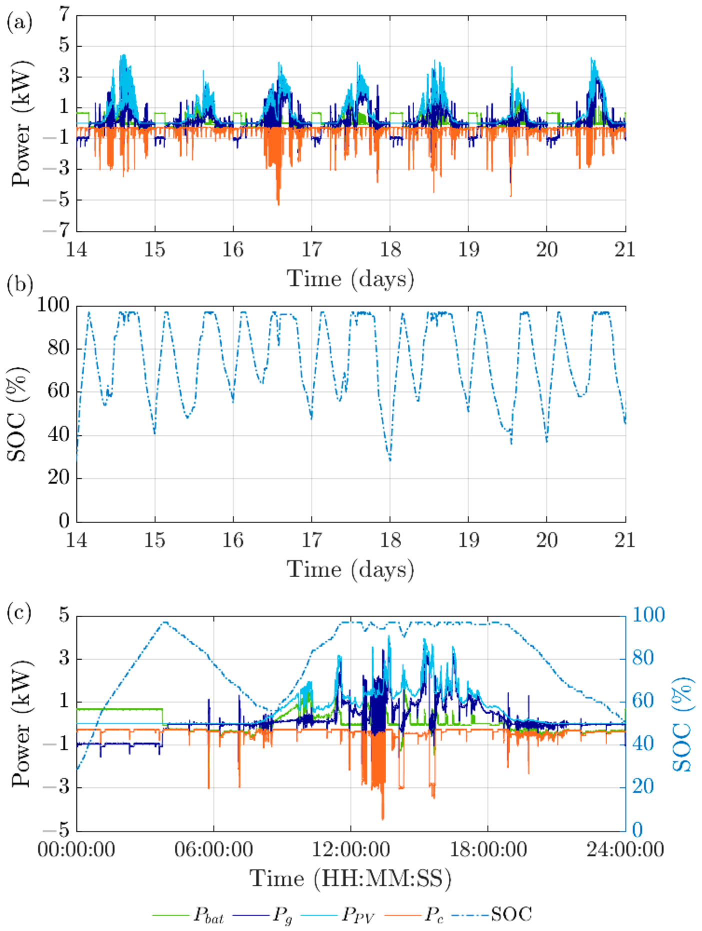


Figure 11. Experimental results of the SLB self-consumption installation: (**a**) SL battery power (P_{bat}), grid power (P_g), PV generation power (P_{PV}), load power (P_c) during one week; (**b**) battery SOC during one week; (**c**) power and SOC during a day [41]. Reprinted with permission of the author.

4.2. EV Fast Charge

By using SLBs it is possible to reduce the required reserved power, which contributes both to cost reduction and to the stability of the distribution network. This is the case when an EV charging station becomes fully occupied, especially when fast charging is utilized. Another example is a charger for urban electric buses [42]. The SLB is charged when the charging station is empty, and the charging power depends on the time until the arrival of the next bus that needs to be quickly charged by high power. The data about the times are known in advance thanks to online tracking of the location of each bus. Idoia San Martín discusses this scenario in detail [13], and results from SLB aging in this application are presented in [41].

4.3. Grid Stability Services

The use of SLBs in power grids can effectively reduce peak load. In addition, it will allow consumers, both small industrial enterprises and households, to optimize their energy demand behavior according to market conditions, thus ensuring optimal energy use. The use of SLBs in stationary grid operations can be divided into the following subsections.

Peak shaving: When using SLB storage to reduce peak demand, it is possible to influence the grid voltage, especially when the voltage drops below a critical threshold. In particular situations wherein the resistance is higher than the reactance and the real power, they have more influence on voltage regulation than the reactive power. At the same time, the frequency in the system can be influenced this way.

Voltage regulation in power systems: Power utilities must supply electricity to customers according to pre-contracted parameters, especially of voltage and frequency. Currently, voltage is controlled at high voltage levels (33 kV and above) by OLTC (on load tap changing) transformers and reactive power generating devices such as shunt capacitors and reactors, static VAR compensators, synchronous condensers, or static synchronous compensators. Battery storage is one way to control voltage levels even on the low-voltage side of the transformer.

Frequency control: Fluctuations in the frequency of the grid are caused by an imbalance between the production and consumption of electricity. If battery storage is connected to the grid, it can be used to flexibly compensate for consumption by either charging or discharging it, allowing the frequency to be kept within the desired range. This process can also be called 'load following', because battery storage varies its performance in response to the immediately available power supply and end-user demand. The advantage of battery storage over conventional sources such as pumped storage is primarily in its potential ramp-up speed, which is on the scale of milliseconds.

Black Start: A device that is capable of a black start must be able to start without external electrical power and be able to supply power to the grid for a defined period of time before the grid is restored after a blackout. SLB storage can be used as a reserve of power and energy within the grid and in the event of a blackout can be used to power transmission and distribution lines or to supply the energy needed to restore power plants to operation.

Electric Energy Time-Shift: The use of electric energy time-shift, known as energy arbitrage, is the purchase of electricity during periods of low cost for the purpose of charging battery storage and then selling the electricity at times when there is a higher demand for electricity on the grid, and the cost per kWh is higher. This method will find application particularly if the percentage of renewable energy sources grows, in which case the amount of energy produced will depend on natural conditions, and often the peak energy supply will not be equal to the peak customer demand.

Transmission Deferral: This application is used to support transformer power from the grid behind the distribution transformer when the power demand is higher than the transmission capability of the transformer. In this case, the batteries are charged during off-peak hours, and power is supplied from the batteries during peak hours to meet the demand beyond the transformer's capability. As electricity consumption is expected to increase in the coming years, it can be expected that the number of days when energy support will be needed will increase. The advantage of this business model is based on the possibility of postponing the upgrading of the transformer station [14].

4.4. The Current State and Future of Second-Life Battery Use

Until now, the potential of SLB was demonstrated in several projects. BMW, Vattenfall and Bosch have installed a 2 MW, 2800 kWh SLB system in Hamburg, Germany, to support the electricity grid. Prismatic cells of 63Ah, MO/NMC-based cathode chemistry from a BMWi3 electric car, are implemented in this storage [43]. Daimler has implemented SLB projects in Hannover and Lunen. Toyota has developed a system using nickel–metal hydride batteries from EVs with an installed capacity 85 kWh, powered by a 40 kW photovoltaic system [44]. A 300 kWh SLB for EV charging support with maximum power output of 520 kW was installed in Prague, Czechia by PRE, ŠKODA AUTO, IBG and AERS [45].

Another example is the Fortum startup project from Sweden, which involves Fortum, Volvo Cars and cleantech company Comsys, in which SLB storage is used in combination with the Landafors hydroelectric power plant. This combination increases the ability of the plant's turbines to regulate the grid and extends their lifetime [46]. An overview of SLB projects up to 2017 is summarized by Martinez-Laserna [47] and R. Reinhardt [48] in their dissertations. A summary of more recent SLB projects for brief comparison is provided in Table 1.

Table 1. Recent second-life battery projects.

Name	Location	Partners	EV model	Capacity	Application	Date
Johan Cruyff Arena [49]	Amsterdam, Netherlands	Eaton, Nissan, BAM The Mobility House, Johan Cruijff Arena	148 Nissan Leaf battery pack	2.8 MWh	PV power supply, emergency supply	2018
EUREF Campus [50]	Berlin, Germany	Audi	Audi	1.9 MWh	Multi-use storage unit compensates for fluctuations in the grid and optimizes energy supply	2019
Former coal-fired power plant in Elverlingsen [51]	Elverlingsen, Germany	Renault	72 batteries Renault Zoes	3 MWh	Energy storage for the power grid	2020
Grid services ENG I E [52]	Olen, Belgium	Renault Connected Energy	Renault Kangoo	720 kWh	Provides firm frequency response to the grid, acting as a revenue generator	2020
Battery Loop Energy Storage System [53]	Mölndal, Sweden	Volvo BatteryLoop Essity	Volvo XC40	NA	PV-powered charging stations for EVs and e-bikes	April 2021
Energy storage system in Herdecke [54]	Herdecke, Germany	Audi RWE	Audi e-tron	4.5 MWh	Frequency response services	November 2021
TGN Energy battery energy storage [55]	Oslo, Norway	Mercedes-Benz Evergy Evyon,TGN	Mercedes Benz	216 kWh	Increased self-consumption	November 2021
Landafors hydropower plant [56]	Landafors, Sweden	Fortum Volvo Cars Comsys	Volvo Cars plug-in hybrids	250 kWh	Offers fast frequency reserve regulation to the power markets	2021

Enel Group’s Second Life project [57]	Melilla, Spain	Enel group	78 Nissan Leaf battery pack	1.7 MWh	Grid stability service—Black start	March 2022
Saxony’s battery storage facility [55]	Freiberg, Germany	Jungheinrich Energy Systems Tricera energy	Jungheinrich forklift batteries	NA	Peak shaving, grid stability services	September 2022
Industrial energy storage system [45]	Prague, Czech Republic	IBG, Škoda, PRE	Škoda Enyaq iV	300 kWh	EV charging station	October 2022

As the number of battery storage systems is currently growing significantly, databases such as [55–57] that attempt to provide an absolute listing of all battery storage systems currently in existence are being created.

One of the obstacles standing in the way of more massive development of SLB is the need for standards targeting second-life batteries. Storage systems composed of SLBs are expected to mix cells of different ages, chemistries, and wiring. If there is no standard for SLB storage, it is understandable that large industrial companies will be reluctant to go down this route. Although the SAE J2997 standard, which specifies battery health and transforming cell labelling, is in the developmental stage, there is still much work to be done in this direction to make SLB storage a mainstream product [44].

5. Economic and Environmental Perspective

Reusing Li-ion batteries at the end of their first life in less intensive application fields could be a way to increase their residual value. Second-life implementation could reduce the acquisition costs of new EV batteries while constituting a cost-profitable replacement for new Li-ion batteries in less demanding applications [7,47,58]. The viability of SLBs is generally evaluated from technical, economic, and environmental points of view.

5.1. Economic Evaluation

The economic assessment represents one of the industry’s most crucial steps to accepting SLBs. Evaluation of the possible market price includes the cost a battery’s purchase (when retired from an EV), transportation, logistics, testing, and refurbishment costs [47,59]. The final price depends on the Li-ion technology, ranging from 111 to 250 $/kWh [59–61].

The profitability analysis of SLBs in a grid-connected stationary unit may provide very different results depending on many factors; these factors were well summarized in the review work introduced by Martinez-Laserna [47]. They include the following:

- Cost structures, i.e., SLBs’ purchase and their market price, the balance of system (BOS) and refurbishment costs.
- Revenue streams, i.e., the target market, rate structures, electricity prices, and ancillary service payment structures.
- Technical parameters, i.e., the SLB’s lifetime, power and energy capabilities, efficiency, and heterogeneity.
- Policies and market-specific conditions, i.e., environmental initiatives, subsidies, and legal requirements.

In the literature published to date, several second-life-based applications are considered economically viable; for example, Debnath et al. considered the first-life application of vehicle-to-grid (V2G) and area regulation in smart grids during second life; Assunçao et al. [62] evaluated residential second-life battery energy storage systems combined with PV systems; Ambrose et al. [63] focused on mini- and micro-grids providing electricity in rural areas of emerging countries. However, the examined condition might differ per country; therefore, an individual assessment of the exact conditions, requirements, and conditions for each application is recommended.

Although one of the accelerating motives for the second-life use of Li-ion batteries from EVs is the possible reduction of the upfront costs of newly produced batteries, currently, the performed studies do not directly confirm this hypothesis. Considering the decreasing trend in battery prices in recent years, it is not obvious that reuse of Li-ion batteries could increase their acquisition costs sufficiently. Depending on the selected technology, the savings on the initial costs of a new EV battery range from 2 to 25% [47,60,64]. The purchase price of a new EV battery will probably not be primarily affected (or only very little) by reuse in a second-life application; therefore, other profiteering methods are still being sought.

5.2. Environmental Impacts

Currently, the most significant reasons for second-life application are the environmental benefits obtained from the principle of reuse in terms of circular economy, where replacing newly produced batteries could reduce energy consumption or pollution [47]. A comprehensive life cycle analysis (LCA) study or individual categorization of environmental impact, including greenhouse gas (GHG) emissions focusing on carbon dioxide (CO_2), acidification, and eutrophication, are commonly used for evaluation. In the published literature, e.g., in work by Cicconi et al. [65] in which the case of smart grid application was studied, the global warming emissions were reduced by ~25% in second-life use (after a first life in PHEV) compared to use of a new battery for this application. Philippot et al. [66] provided an LCA assessment wherein the second life reduces the impact of ozone formation, particulate matter, human toxicity (non-cancer and cancer) effects, freshwater eutrophication and ecotoxicity, acidification, and minerals and metal resources' use. The current present results agree that second-life use could provide powerful environmental benefits.

Nowadays, there is a combined impact for Li-ion technology: secondary application of batteries represents a suitable environmental solution until recycling Li-ion batteries becomes economically feasible. Only a few economic evaluations of current recycling approaches have been studied so far; it is expected that the research focus on this topic will grow with the increasing amount of waste batteries in the following years [67].

6. Discussion

SLBs are a perspective technology, though there are some remaining challenges that need to be overcome before their mass acceptance, commercialization, and utilization.

Firstly, there is still a large number of second-life batteries available, thus preventing a significant scaling up which would positively impact their economic feasibility. However, this situation will gradually change as EVs are increasingly adopted resulting in a progressive increase in availability of SLBs. Secondly, but even more importantly than the previous aspect, access to the batteries (from both a technological and intelligence standpoint) is restricted to the EV manufacturers. This can also be observed from Table 1, where for all the second-life battery demonstrators, at least one partner is an EV manufacturer. Thus, at the moment we are dealing with a quasi-monopolistic business model, and without direct collaboration with the OEM, it is difficult for start-ups entering the market.

Another aspect which must be discussed is the suitability of EV-retired batteries for second-life applications. While in most cases, the EV battery degradation beyond 20% capacity fade is not accelerated (i.e., there is no change in the degradation trajectory once the battery reached 20% capacity fade) [68], Gismero recently presented laboratory results in [33] showing very fast capacity and resistance degradation once an EV battery reached approximately 20% capacity fade.

This behavior imposes even more stringent requirements on the effectiveness of SOH estimation methods which are being used to determine the battery SOH at the transition from first life to second life, and for monitoring the SOH during the battery second life. Thus, if the degradation behavior presented in Figure 12 is not unique (i.e., valid only for the few tested samples), it might become necessary to develop SOH estimation methods which are tailored for EV batteries in order to capture such a behavior. Independent of the used SOH estimation method, the challenge of the unknown battery history remains, and the future degradation trajectory, in second-life applications, can vary even though the cells with similar capacity or internal resistance were matched for second-life applications. This challenge could be addressed by introducing a battery passport which would carry the information of the battery history, allowing for an effective and simplified screening procedure at the beginning of the battery's second life. However, introduction of the battery passport requires some sort of standardization of measurements, state estimation, data processing and data storage across manufacturers or collaborative groups. Meanwhile, it is necessary to develop and tailor screening methods that allow for cheap and high-throughput screening with accurate assessment of the battery state.

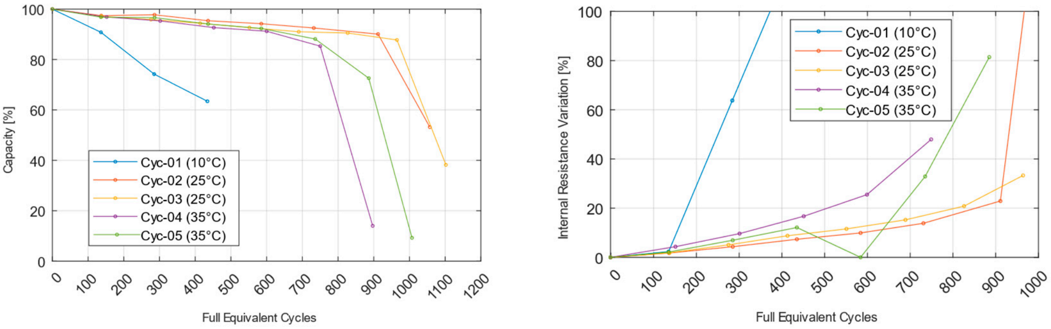


Figure 12. Capacity fade (**left**) and internal resistance increase (**right**) trends for an EV battery illustrating fast degradation once the battery reached approximately 20% capacity fade; capacity measured at 25 °C and C/5 and resistance measured at 25 °C and 50% SOC [33]. Reprinted with permission of the author.

Although SLBs are in their infancy and their capabilities are still being tested within the framework of pilot projects, the benefits of reusing technology are evident. Considering the economic perspective, secondary use is regarded as beneficial for many applications, including smart grids, energy storage systems combined with PV applications, and mini and micro-grids providing electricity in rural areas. For a detailed description of profitability analysis, it is necessary to evaluate each scenario of the selected application individually, considering its technical parameters, revenue streams, etc. Nevertheless, the savings on the initial costs of a new EV battery range can range from 2 to 25%. From the environmental point of view, the SLB application brings many benefits; it directly supports a circular economy principle that focuses on eliminating waste and pollution, circulating products and materials, and regenerating nature. Replacing newly produced batteries reduces energy consumption and pollution (mainly in global warming emissions). In the case of the smart grid application studied, the emissions were reduced by ~25% for the SLB compared to using a new battery for this application. Similar results are expected in other applications of this technology.

In the current situation, SLBs represent a suitable solution until recycling Li-ion batteries becomes economically feasible. However, recycling evaluations are in their infancy, and a comprehensive summary will make it possible to assess them after the overall increase in EOL batteries and the increase in the share of electromobility in the automotive market.

Author Contributions: Conceptualization, K.N., A.P. and V.K.; methodology, K.N. and A.P.; resources, K.N. and A.P.; data curation, K.N. and A.P.; writing—original draft preparation, K.N. and A.P.; writing—review and editing, D.-I.S. and V.K.; supervision, D.-I.S. and V.K.; project administration, K.N. and V.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS23/065/OHK3/1T/13.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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