

Article

Experimental Validation of a Rapid Pre-Sorting Methodology for Small-Capacity Lithium-Ion Cells

Kristjan Veidenberg, Külli Hovi, Jaak Jõgi, Andres Annuk, Olga Panova and Mart Hovi *

Institute of Forestry and Engineering, Estonian University of Life Sciences, 51006 Tartu, Estonia; kristjan.veidenberg@emu.ee (K.V.); kylli.hovi@emu.ee (K.H.); jaak.jogi@emu.ee (J.J.); andres.annuk@emu.ee (A.A.); olga.panova@emu.ee (O.P.)

* Correspondence: mart.hovi@emu.ee

Abstract

The reuse of small-capacity lithium-ion cells recovered from disposable e-cigarettes is limited by the lack of rapid and low-cost screening methods. This study evaluates a low-complexity 3-30-3 pre-sorting methodology based on a 30 s DC load pulse and a 3 min rest period applied to series connected cells under identical current conditions. Generic 13350-type cells with a nominal capacity of approximately 850 mAh were tested, and cell suitability was assessed from voltage drop, effective direct-current resistance, and stability over repeated load cycles. In the tested batch, the coefficient of variation of the effective resistance reached 28–35%, indicating substantial cell-to-cell variation within this pilot sample. Repeated loading improved discrimination between stable and degraded cells and enabled selection of a compatible subset for assembly into a 3S3P battery pack. The assembled pack operated successfully as a power source for a FläktWoods 227VM pressure controller in biomass drying monitoring. The proposed method does not replace full battery diagnostics, but it provides a practical first-stage filter that can reduce testing time by more than 90% and improve the safety of second-life cell grouping.

Keywords: DC pulse test; 3-30-3 protocol; diagnostic algorithm; small-capacity cells; e-cigarette waste; effective DC resistance; pre-sorting; circular economy

1. Introduction

Disposable e-cigarettes have become a significant waste-management challenge in recent years. When they enter mixed household waste streams, the lithium-ion batteries they contain can cause fires in waste handling facilities and contribute to the release of heavy metals, plastics, and nicotine residues into the environment [1]. At the same time, these devices often contain still-functional lithium-ion cells whose reuse potential remains largely unrealized.

It was estimated that in 2024 approximately 369.1 tonnes of e-cigarettes entered mixed household waste in Estonia (the average Estonian resident discards about 0.27 kg of e-cigarettes into mixed household waste annually) [2]. Each of these devices contains a reusable lithium-ion cell, typically with a capacity of about 500 mAh. Although such cells are often still functional after single use, their large-scale reuse is hindered by time-consuming and costly testing procedures.

Despite the widespread availability of lightly used lithium-ion cells, there is no recognized standard for their large-scale second-life deployment. Although international

Academic Editor: JongHoon Kim

Received: 16 June 2026

Revised: 3 July 2026

Accepted: 6 July 2026

Published: 10 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

standards exist for lithium-ion battery testing (e.g., IEC 62660), they are primarily intended for quality control of new cells [3]. Such methods are time-consuming and require sophisticated laboratory equipment, making them economically impractical for rapid screening of discarded e-cigarette batteries. Therefore, fast and resource-efficient diagnostic methods are needed to support rapid and inexpensive assessment of waste-directed cells for reuse purposes.

Methods based on short direct-current pulses offer a potential solution. Because battery models differ in complexity and application, simplified electrical circuit models are often preferred for diagnostic and simulation tasks where rapid evaluation is required, while more detailed electrochemical models are reserved for comprehensive battery analysis [4]. Previous studies have used such methods to assess battery condition and safety through longer pulse sequences [5]. In this work, the problem is approached from the opposite direction: whether a much shorter 30 s load pulse is sufficient to differentiate the electrochemical condition of used cells and enable rapid pre-sorting. Compared with electrochemical impedance spectroscopy (EIS), DC pulse methods are considerably faster while still providing sufficient accuracy for comparative battery evaluation [6].

Recent research highlights the growing importance of efficient battery utilization and energy storage solutions in both electrified power systems and renewable energy integration, emphasizing the need for rapid, reliable methodologies to assess lithium-ion cells for second-life applications [7,8]. The growing adoption of second-life lithium-ion batteries in stationary energy storage and hybrid energy storage systems further emphasizes the need for reliable, rapid screening methodologies that enable safe cell selection and support circular economy strategies [9].

The aim of this work is to validate a low-complexity pre-sorting methodology based on load pulses applied in a series-connected arrangement. The proposed approach enables comparison of cell voltage behaviour under identical current conditions and assessment of direct-current internal resistance (DCIR) within a short time. The methodology is not intended as a complete diagnostic method, but rather as an initial filter for identifying obviously unsuitable cells and reducing the extent of subsequent in-depth testing in practical second-life workflows. Efficient and accurate sorting is a key prerequisite for the safe and economical second-life utilization of retired lithium-ion batteries, as it directly influences battery regrouping, service life, and operational reliability in subsequent applications [10,11].

The novelty of this work lies not in replacing conventional state-of-health diagnostics but in addressing a different and underexplored practical challenge: rapid first-stage pre-sorting of large quantities of small-capacity second-life lithium-ion cells with unknown usage history. The proposed methodology combines simultaneous series-connected testing, a simple 3-30-3 DC pulse protocol, and experimental validation in a practical application, demonstrating that unsuitable cells can be identified within minutes before more resource-intensive diagnostic procedures are applied.

2. Materials and Methods

2.1. Tested Cells and Device Setup

The study used generic 13350-type lithium-ion cells (3.7 V, approximately 850 mAh) recovered from disposable e-cigarettes (Table 1). The exact manufacturer and cell chemistry were not specified on the recovered cells; therefore, they are treated here as generic small-format lithium-ion cells. In the initial stage, approximately 40 cells were fully charged and subjected to a first screening. Approximately 15% of the cells were excluded because their measured voltage was below 2.5 V. This limit was selected as a conservative exclusion threshold for deeply discharged lithium-ion cells, for which copper dissolution, elevated self-discharge, or other irreversible degradation mechanisms may already be a

concern. About 10% were estimated to be older than four years based on device-generation information and external markings, and approximately 10% were excluded because of visible physical criterion made it possible to focus on degradation arising from usage history and to reduce the effect of calendar ageing. For defining the screening threshold, a value of 45 mΩ was defined as the baseline internal resistance for a new, pristine cell of this specific model, derived from manufacturer specifications and initial benchmark measurements.

Table 1. Summary of the tested cell type and preliminary exclusion criteria.

Parameter	Parameter
Cell format	Generic 13350-type lithium-ion cell recovered from disposable e-cigarettes
Nominal voltage	3.7 V
Nominal capacity	Approximately 850 mAh
Baseline internal resistance (fresh cell)	45 mΩ
Manufacturer/model	Not specified on recovered cells
Chemistry	Lithium-ion; exact cathode chemistry not specified
Initial sample	Approximately 40 cells
Exclusion criteria	Voltage below 2.5 V, estimated age above four years, or visible physical damage
Detailed test sample	13 cells physically connected; 11 channels retained for resistance analysis

A series-connected test platform was constructed for the experiment (Figure 1), enabling synchronized data acquisition from up to 14 units. The system consists of three parts: battery holders, a controllable load circuit, and a microcontroller-based data acquisition node.

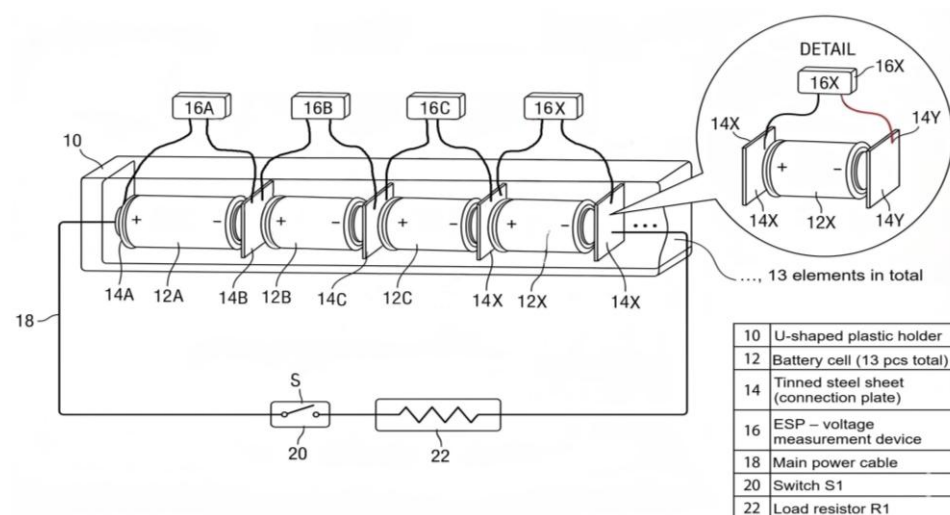


Figure 1. Schematic circuit diagram and data acquisition system of the rapid diagnostic test bench for battery cells.

2.2. Data Acquisition and Data Processing

Measurement data were transmitted via Wi-Fi to the ThingsBoard IoT platform at a recording frequency of 0.1 Hz. Due to the noise sensitivity of the ESP-01 microcontroller ADC, software smoothing was applied to the readings already at the data generation stage. To correct irregular timestamps caused by network delays, the data were post-processed

and normalized to a 10 s time step. Missing data points were filled by linear interpolation, ensuring a unified time axis for comparison between cells. Based on the calculated voltage drop (ΔU), the effective DC resistance of each cell was determined. Because of the limited sampling frequency, the result is treated as an effective resistance rather than a purely ohmic component, as it also includes fast polarization processes and reflects the real battery behaviour under load. All 13 cells were physically connected during the experiment; however, for two measurement channels the recorded time series were not of sufficient quality for analysis. For channel VA, the readings were unstable and noisy, whereas for channel VD no reliable time series was obtained for most of the test. Therefore, these two cells were excluded from the effective-resistance calculations and from the summary tables.

2.3. Experimental Conditions

The measurements were carried out in an indoor environment at 22 ± 1 °C. Before the test, all cells were charged to a high state of charge (SoC 90–100%, ≥ 4.1 V). During the test, the applied load current was 1.0 A, corresponding to a 1.2 C regime.

2.4. Testing Procedure

A two-stage testing procedure based on repeated load pulses was applied to sort the cells. This approach enables differentiation between sound cells and those whose parameters have begun to degrade. In addition, the methodology makes it possible to assess effective DC resistance and voltage-drop dynamics (ΔU) of the cells within a very short time, making the process scalable for larger quantities. Repeated pulse testing is particularly relevant because cell-to-cell variations in internal resistance and dynamic voltage response become increasingly important when cells are grouped into battery packs, directly affecting current sharing and long-term operational stability [12].

The 30 s load phase is derived from the HPPC protocol [13]. A 3 min rest phase was selected based on the three-stage nature of battery voltage recovery. While ohmic recovery occurs within seconds and the charge-transfer and double-layer relaxation stabilizes over a few minutes, ionic diffusion processes may continue for much longer [14]. At the same time, a 30 s load phase is sufficiently short to avoid significant discharge (approximately 1% SoC reduction) and thermal effects. Given the 0.1 Hz sampling interval, the methodology does not allow the ohmic voltage drop and polarization processes to be isolated from one another, but rather measures their combined effect in a stabilized phase.

Initial Testing Under Moderate Load

In the first stage of the experiments, a 30 s load pulse of approximately 1.2 C (1.0 A) was applied to the cells. A variable load resistor (maximum resistance 150 Ω) was used to set the load precisely. Considering the total voltage of the series-connected cells (48–54 V), this ensured the desired current level.

The measurement was carried out according to the 3-30-3 protocol:

- During the first 3 min no-load period, the open-circuit voltage (U_0) of the cell is determined, forming the basis for the subsequent voltage-drop calculation.
- During the following 30 s load phase (1.0 A), the voltage dynamics are recorded and the effective DC resistance of the cell is determined at the end of the 30th second.
- The process ends with a 3 min recovery period, during which the post-load voltage is recorded in order to assess recovery dynamics and the electrochemical condition of the cell.
- The measurement cycle was repeated to verify repeatability and result stability by applying the same time protocol after a short rest interval

3. Results

3.1. Voltage Characteristics of the Load Test

Despite identical loading conditions, clear differences appeared in the voltage curves. Upon load application, a voltage drop (ΔU) occurred, directly related to the effective DC resistance of the cell under the applied pulse. During the 30 s load phase, the voltage continued to decrease due to electrochemical discharge and polarization. The average voltage drop among the observed cells ranged from 0.05 V to 0.19 V, as shown in Figure 2.

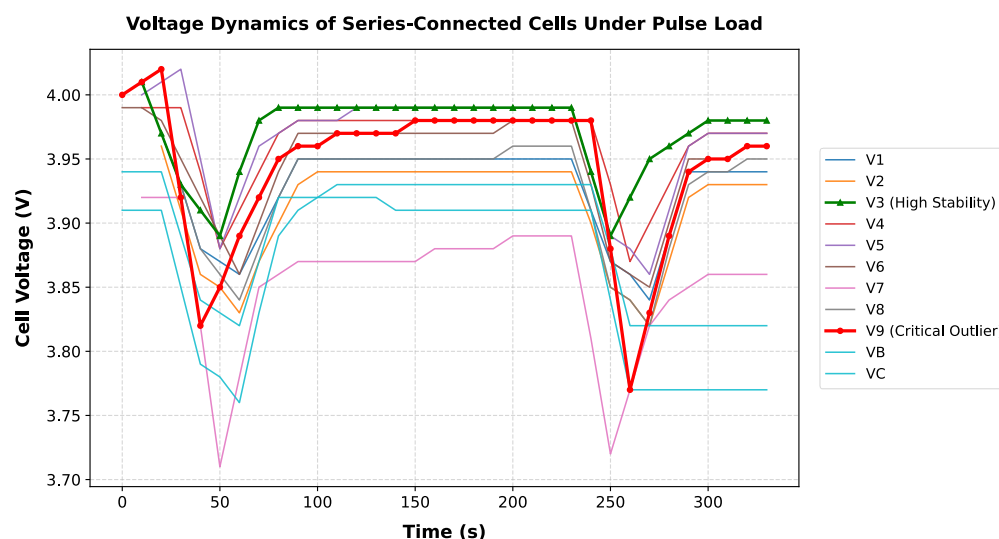


Figure 2. Voltage changes of 13 series-connected cells during the 3-30-3 test.

3.2. Cell Grouping and Internal Resistance

The effective DC resistance of each cell was determined from the ratio of measured voltage drop to applied current. Here, U_0 is the open-circuit voltage of the cell immediately before load application, U_{load} is the voltage under load (here taken as the end value at the end of the 30 s pulse), and I is the applied current. The result is expressed in $m\Omega$ and reflects the total resistance response measured under the conditions of the given pulse (ohmic + polarization component). The obtained resistance values make it possible to perform an initial classification of cells according to their state of health (SoH) and suitability for second-life use (Table 2).

Table 2. Results of internal resistance calculations during the first loading cycle.

Cell	U_0 (V)	U_{load} (V)	ΔU (V)	R_{DCI} ($m\Omega$)
V1	3.97	3.86	0.11	110
V2	3.96	3.83	0.13	130
V3	4.01	3.96	0.05	50
V4	3.99	3.87	0.12	120
V5	4.02	3.87	0.15	150
V6	3.98	3.86	0.12	120
V7	3.92	3.83	0.09	90
V8	3.97	3.84	0.13	130
V9	4.02	3.83	0.19	190
VB	3.91	3.76	0.15	150
VC	3.94	3.82	0.12	120

3.2.1. Conclusions from the First Loading Cycle

The initial voltage at 09:06:40 was taken as the moment immediately before the voltage began to drop sharply. The end of loading at 09:07:20 corresponds to the point 40 s later when the voltage had reached its lowest stable point before recovery began (starting at 09:07:30). The effective DC resistance values calculated from the first loading cycle ranged from 50 mΩ to 190 mΩ. Cell V3 stands out due to its low resistance (50 mΩ), which may indicate either a nearly new cell or a sensor offset. Although 13 cells were included in the experiment, the tables present results for 11 cells because the data from channel VA were unstable during the relevant interval and channel VD did not yield a sufficiently reliable time series for analysis. Therefore, both channels were excluded from the effective-resistance calculations and the tables (Table 3).

Table 3. Results of internal resistance calculations during the second loading cycle.

Cells	U_o (V)	U_{load} (V)	ΔU (V)	R_{DCI} (mΩ)
V1	3.95	3.84	0.11	110
V2	3.94	3.82	0.12	120
V3	3.99	3.95	0.04	40
V4	3.98	3.86	0.12	120
V5	3.99	3.86	0.13	130
V6	3.98	3.85	0.13	130
V7	3.89	3.82	0.07	70
V8	3.96	3.82	0.14	140
V9	3.98	3.75	0.23	230
VB	3.91	3.74	0.17	170
VC	3.93	3.82	0.11	110

3.2.2. Conclusions from the Second Loading Cycle

The initial voltage at 09:10:10 is the final moment at which the battery voltage had recovered and stabilized after the first rest period, immediately before the next drop. The end of loading at 09:10:50 marks the point where the load had been applied for 30–40 s and the voltage had reached its minimum before the second recovery phase began at 09:11:00. Compared with the first test (09:06:40), interesting dynamic changes are visible. Cells V1, V4, and VC can be considered highly stable. Their effective resistance remained nearly identical, with a difference of only 0–10 mΩ, which may indicate high-quality cells that are less prone to heating under repeated loading.

The behavior of V9 is the most concerning across the two cycles: its effective resistance increased from 190 to 230 mΩ, indicating an accelerating polarization dynamic. Unlike V1 and V4, which remained identical in both cycles, V9 did not stabilize sufficiently during the three-minute rest period. V3 remained very low at 40–50 mΩ. If this is not a measurement error, it suggests that V3 was the best-performing cell in the sample. The initial voltages in the second cycle were approximately 0.02–0.05 V lower than in the first cycle because part of the energy had already been consumed by the first pulse. Considering that, for a cell with a nominal capacity of 850 mAh, one 30 s pulse at 1.0 A consumes approximately 8.3 mAh, i.e., about 1% of nominal capacity, a small increase in effective resistance after two consecutive pulses due to an approximately 2% SoC decrease is expected. Therefore, the higher resistance measured in the second cycle should not automatically be interpreted as a sign of degradation; however, a clearly larger change, such as the 40 mΩ increase observed in V9, likely indicates additional polarization effects or internal instability of the cell.

In addition to the degradation observed in cell V9, cell V7 exhibited a critical voltage depression under the applied load pulse. While the majority of the cells maintained terminal voltages well above 3.75 V, the voltage of cell V7 dropped sharply to 3.71 V during the first cycle and further collapsed to a minimum of 3.51 V in the subsequent loading phase. This represents the lowest transient voltage captured across the entire operational batch. This behavior indicates an excessively high static internal resistance and severe cell capacity depletion, making cell V7 equally unsuitable for safe second-life pack integration. The comparison of the effective resistance changes observed between the two loading cycles is summarized in Table 4.

Table 4. Comparison of internal resistance results across loading cycles.

Cell	Cycle 1 (Rdci)	Cycle 2 (Rdci)	Change(mΩ)	Stability
V1	110	110	0	Excellent
V2	130	120	−10	Good
V3	50	40	−10	Exemplary
V4	120	120	0	Excellent
V5	150	130	−20	Good
V6	120	130	+10	Good
V7	90	70	−20	Good
V8	130	140	+10	Good
V9	190	230	+40	Critical
VB	150	170	+20	Satisfactory
VC	120	110	−10	Good

3.3. Analysis of Cell Voltage Dynamics and Resistance Dispersion

Analysis of the graphs shows that the stability of voltage change during repeated load cycles is an important indicator of cell quality. The 7 min test period, consisting of two 30 s load pulses separated by a 3 min rest phase, made it possible to identify electrochemical stability features that a single test might not reveal.

The results showed that for high-quality cells (e.g., V3), the voltage drop in both cycles was almost identical (± 0.01 V), and the voltage stabilized quickly, reaching a steady level within the first 10 s. This may indicate a cell with low polarization resistance and stable internal chemistry. In degraded cells (e.g., V9), the second load cycle produced a significantly deeper voltage drop (approximately 40 mΩ increase in effective resistance). The increase in dispersion during the second cycle was caused mainly by the sharp resistance rise in one critically worn cell, V9.

Monitoring the entire test period confirmed that defective cells are unable to fully recover their potential during the 3 min rest period and that each subsequent load pulse deepens the voltage drop. The difference between stable and degraded cells demonstrates that a repeated-pulse methodology is necessary for distinguishing between “apparently healthy” cells and cells with substantial internal wear that could remain undetected in a single test.

The 3-30-3 methodology can function as a diagnostic algorithm in which effective resistance calculation is supplemented by monitoring of voltage dynamics under load. The experimental results showed a large variation in resistance values: the standard deviation was about 35 mΩ, and the relative dispersion (coefficient of variation) reached 35%.

By comparison, new cells typically show resistance dispersion below 5% owing to precise manufacturing processes. Within a single production batch manufactured in the same factory, on the same line, and with the same material supply chain, the variation is typically in the range of 1–3% [12]. The 35% dispersion observed in the tested cells is a clear sign of substantial non-uniformity. Without pre-sorting, using such a heterogeneous

batch in a battery pack would be both unsafe and technically unreasonable, because large differences in resistance would lead to uneven loading of the cells. In the assembly of new commercial battery packs, cells with internal-resistance deviations above 2–3% are generally considered unsuitable [15]. The statistical summary of the effective resistance measurements is presented in Table 5.

Table 5. Statistical summary of internal resistance measurement results.

Cell	Cycle 1 (R_{DCI})	Cycle 2 (R_{DCI})	Change
Mean ($\bar{x}$)	120.9 m Ω	124.6 m Ω	+3.1%
Standard deviation (s)	35.6 m Ω	44.1 m Ω	+23.9%
Relative variation (CV)	28.8%	34.6%	+20.1%

To evaluate whether repeated pulse loading affected the average effective DC resistance, the RDCI values obtained during the first and second loading cycles were compared using a paired Student's t -test. No statistically significant difference in the mean RDCI was observed ($t(10) = -0.166$, $p = 0.871$). The standard deviation (s) was calculated as:

$$s = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n - 1}}$$

where:

x_i is the resistance of an individual cell;

$\bar{x}$ is the mean resistance of all cells;

n is the number of analyzed cells (11). Since the statistics were calculated from a sample rather than an entire population, the denominator ($n - 1$) was used (Bessel's correction).

The coefficient of variation (CV) was calculated as:

$$CV = \frac{s}{\bar{x}} \times 100\%$$

where:

s is the sample standard deviation;

$\bar{x}$ is the arithmetic mean of the sample.

Although the average RDCI remained essentially unchanged, the variability increased during the second loading cycle. The standard deviation increased from 35.6 m Ω to 44.1 m Ω and the coefficient of variation from 28.8% to 34.6% (Table 5). This increase was primarily caused by the pronounced deterioration of cell V9, whereas the majority of the remaining cells exhibited only minor changes.

These observations indicate that the main practical advantage of the repeated 3-30-3 pulse protocol is not a statistically significant shift in the average resistance, but an improved ability to distinguish stable cells from severely degraded ones. Repeated pulse loading therefore provides additional diagnostic information that enhances the effectiveness of first-stage screening for second-life battery applications.

3.4. Test Efficiency and Methodological Analysis

One of the main objectives of this work was to reduce testing complexity and time consumption while preserving sufficient diagnostic accuracy. The series-connected topology can be considered efficient in terms of time reduction. The time savings are substantial because simultaneous testing of 13 cells in a series arrangement reduced total testing time by more than 90% compared with individual testing.

A second advantage of the method is the uniformity of testing conditions. In this configuration, errors caused by fluctuations of the current source or by differences in conductor resistance are excluded, making the comparison of voltage-drop and internal-resistance indicators more reliable.

The hardware simplicity of the method, requiring only a single controllable load circuit, makes the system easily scalable for the initial sorting of large quantities of cells. Although the 0.1 Hz data acquisition step in rapid diagnostics introduces some uncertainty compared with laboratory precision measurements, the use of two load cycles together with statistical dispersion analysis in Table 5 helps mitigate this risk. Cells with broken circuits or critically low voltage, which could interfere with the series test, are identified and removed systematically during the initial voltage-screening stage of the methodology (Section 2.1). This initial matching step is particularly important because cell-to-cell variations are unavoidable, arising from both manufacturing tolerances and non-uniform ageing during service, making appropriate cell selection a fundamental prerequisite for safe and reliable battery-pack operation [16].

However, it is critical to emphasize that this rapid 3-30-3 pulse screening serves strictly as a preliminary high-speed filter and is inherently insufficient as a standalone qualification protocol for second-life battery pack assembly [4]. Short-duration direct-current pulses evaluate the immediate effective internal resistance and localized polarization dynamics, but they remain fundamentally incapable of determining the actual remaining capacity (Ah) of the cells or detecting latent structural defects such as localized lithium plating or micro-gas formation [6,12]. To achieve a safe and comprehensive cell qualification framework, this first-stage screening must be appended by secondary diagnostic layers. Specifically, a full galvanostatic charge–discharge cycling test at a conservative 0.2 C rate remains mandatory to map the absolute capacity fade and ensure accurate capacity matching within the parallel branches of the 3S3P pack. Furthermore, for high-reliability second-life deployments, integrating electrochemical impedance spectroscopy (EIS) is necessary to isolate ohmic, charge-transfer, and solid-electrolyte interphase (SEI) resistance components, allowing for the detection of underlying thermal runaway triggers that short-duration time-domain pulses cannot uncover [6,12].

3.5. Application Example

To verify the methodology in practice, a battery pack in 3S3P configuration (3 in series, 3 in parallel) was assembled from the nine cells that showed the smallest and most mutually consistent voltage drop and effective DC resistance values across two consecutive load cycles. Cell V9 was excluded because of its critical behaviour, and cell VB was also left out because its stability was borderline and its resistance was higher and less stable than in the rest of the selected group.

This structure was chosen to achieve a nominal voltage of 11.1 V and a total capacity of 1.5 Ah, which is optimal for powering low-energy industrial sensors. To ensure safety and protect the cells against deep discharge, the battery pack was equipped with a battery management system (3S BMS Balance 10A Li-ion Lithium Battery Charger Protection Board). This module provides continuous voltage monitoring and protects the internal wiring and electronics against possible short circuits and overcurrents. This additional layer of protection is essential to reduce risks that cannot be detected by the primary pulse test alone. The battery pack was connected to a FläktWoods 227VM pressure controller used under real conditions for air-pressure monitoring in the biomass drying process. During the test period, the system demonstrated good stability and the battery pack was able to ensure uninterrupted operation of the controller throughout the multi-day observation period without system failures. The controller's low current consumption matched

well with the profile of reused cells, where the aim is long-term and stable discharge behaviour. This application example illustrates that cells grouped using the 3-30-3 protocol offer potential for economically efficient use in autonomous measurement systems.

This approach directly supports the objectives of the European Union Battery Regulation (Regulation (EU) 2023/1542), which prioritizes battery reuse and second-life applications, thereby advancing the circular economy and reducing the environmental impact of e-waste [1]. At the same time, safety incidents observed during the experimental series indicate that, at its current stage, the method should be regarded only as a primary diagnostic filter. This confirms the need to combine rapid pre-sorting with continuous voltage monitoring and hardware-based safety solutions in order to ensure safe secondary-use applications.

4. Discussion

Although the present study confirms the effectiveness of the 3-30-3 methodology for rapid grouping of cells based on capacity and internal resistance, it must be emphasized that the method functions as a primary diagnostic filter rather than a complete solution. As noted in other studies [5], DC pulses do not detect all hidden safety risks. For example, lithium plating or gas formation may remain unnoticed and can later lead to cell instability.

A complete cell diagnostic procedure also requires monitoring of the self-discharge rate. This is important for ensuring balance and stability in battery packs. A single short-term measurement also does not allow prediction of the remaining useful life of a battery and does not identify the knee point of the degradation curve, where cell parameters begin to deteriorate sharply. In addition, rapid testing may fail to detect thermal instability and lithium plating. These are precisely the main safety risks in second-life applications. Therefore, the 3-30-3 protocol is a valuable tool for large-scale initial sorting, but in practical implementations it must operate together with physical protection (BMS) and additional long-term monitoring procedures. A battery management system (BMS) provides continuous monitoring of battery parameters together with state-of-charge and state-of-health estimation, thereby supporting the safe operation of lithium-ion battery packs during second-life applications [17].

In this study, a sampling frequency of 0.1 Hz (one reading every 10 s) was used, which is optimized for low-complexity systems. Within the framework of the present methodology, the longer time scale employed allows assessment of the total internal resistance (RDCI) of the battery. In practical applications, this value is more informative because it includes not only ohmic resistance but also chemical polarization and charge-transfer delays. This approach provides a more realistic picture of battery performance under sustained load, which is important for cell grouping and for ensuring the long-term stability of the battery pack.

In addition, the gradual implementation of the European Union Battery Regulation must be taken into account. Regulation (EU) 2023/1542 provides that, from 18 February 2027 onward, portable batteries incorporated into products must be readily removable and replaceable by the end user [18]. In the longer term, this may reduce the number of hard-to-remove cells from small devices, including e-cigarettes, entering the waste stream. As a result, the application scope of the methodology investigated in this work may narrow in the future, specifically in the context of cells recovered from disposable e-cigarettes. However, this does not make the method irrelevant for the current waste stream or for the rapid pre-sorting of already available used cells, and the underlying methodological principle remains transferable to other small portable lithium-ion cells.

From a regulatory perspective, it should also be emphasized that an operator preparing a used battery for reuse or repurposing may become a producer under Regulation

(EU) 2023/1542 and must therefore meet the applicable safety and conformity requirements [1]. Consequently, the 3-30-3 pulse test used in this work cannot be regarded as a complete assessment of SoH, capacity, self-discharge, or safety. The U.S./Canadian standard UL 1974 [18] addresses the sorting and evaluation of repurposed batteries, modules, and cells, emphasizing controlled visual and electrical testing [12]. The approximately 1.2 C 30 s pulse used in the present work should therefore be interpreted primarily as a rapid comparative stress test rather than as a conservative capacity or lifetime assessment procedure. For cells with unknown use history, such a pre-filter should be followed by lower-current verification tests, continuous voltage monitoring, and protective circuitry before the cells are used in a battery pack.

The sample size ($n = 13$) limits the generalizability of the statistical conclusions. An interesting direction for future work would be to determine whether the 28–35% variation observed here is characteristic specifically of e-cigarette batteries as a product category or whether it reflects a broader pattern across used consumer electronics batteries in general.

5. Conclusions

The wider adoption of reused e-cigarette cells has been hindered by the lack of reliable rapid diagnostic methodologies, making testing costs disproportionately high. This work shows, within a small pilot sample, that a pulse test applied in a series-connected arrangement does not replace full diagnostics but can serve as an initial filter. It allows obviously unsuitable cells to be separated and can reduce the amount of subsequent in-depth testing required. The use of repeated load cycles proved important. Although a small increase in effective resistance may already appear in the second cycle solely because of an approximately 2% SoC decrease, this does not explain the sharp increase in the resistance of V9 from 190 to 230 m Ω or the increase in relative variation from 28.8% to 34.6%. These are precisely the kinds of effects that a single test would not reveal.

The observed effective-resistance dispersion of 28–35% in the tested batch, compared with the typical variation of below 5% reported for new cells [8], indicates that directing e-cigarette-derived cells to second-life use without thorough dynamic screening may be high-risk.

The series connection reduces testing time by more than 90%, but the limited sample size ($n = 13$) does not yet allow broad generalization of the results.

Author Contributions: Conceptualization, methodology, investigation, A.A.; formal analysis, A.A.; writing—original draft preparation, writing—review and editing, K.V., K.H., J.J., O.P. and M.H.; supervision, M.H. and A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Energy Efficiency and Renewable Energy Research Infrastructure project of the Estonian Research Council under Grant TARISTU24-TK12.

Data Availability Statement: The experimental data underlying this study and the real-time visualized voltage graphs are publicly available on the ThingsBoard cloud platform (Estonian University of Life Sciences). Interested readers can examine the voltage behaviour and internal-resistance measurement results of the cells at the following address: ThingsBoard public dashboard (<http://informatics2.emu.ee:8080/dashboard/a03f5350-53eb-11f0-86c9-3d5c4282d3a1?publicId=0c974740-5ccb-11ec-b966-41b851f4d583> (accessed on 21 April 2026)).

Acknowledgments: During the preparation of this manuscript, the authors used ChatGPT (OpenAI, GPT-5.5) solely for linguistic and structural editing. The authors reviewed and edited the output and take full responsibility for the content of this publication.

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

References

1. European Parliament and Council of the European Union. *Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 Concerning Batteries and Waste Batteries, Amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and Repealing Directive 2006/66/EC (Text with EEA Relevance)*; European Union: Brussels, Belgium, 2023.
2. Jäätmeanalüüs, O.Ü. *National Waste Composition Study*; Estonian Environment Agency: Tallinn, Estonia, 2025.
3. IEC 62660; Secondary Lithium-Ion Cells for the Propulsion of Electric Road Vehicles. International Electrotechnical Commission: Geneva, Switzerland, 2021.
4. Nikdel, M. Various battery models for various simulation studies and applications. *Renew. Sustain. Energy Rev.* **2014**, *32*, 477–485. <https://doi.org/10.1016/j.rser.2014.01.048>.
5. Gasper, P. Searching for a Pulse: Evaluating the Use of Rapid DC Pulses for Diagnosing Battery Health, State-of-Charge, and Safety. *J. Electrochem. Soc.* **2025**, *172*, 060503. <https://doi.org/10.1149/1945-7111/addd50>.
6. Andre, D.; Meiler, M.; Steiner, K.; Wimmer, C.; Soczka-Guth, T.; Sauer, D.U. Characterization of high-power lithium-ion batteries by electrochemical impedance spectroscopy. I. Experimental investigation. *J. Power Sources* **2011**, *196*, 5334–5341. <https://doi.org/10.1016/j.jpowsour.2010.12.102>.
7. Meister, R.; Yaïci, W.; Moezzi, R.; Gheibi, M.; Hovi, K.; Annuk, A. Evaluating the Balancing Properties of Wind and Solar Photovoltaic System Production. *Energies* **2025**, *18*, 1871. <https://doi.org/10.3390/en18071871>.
8. Tahir, M.; Ahmed Khan, S.; Khan, T.; Waseem, M.; Khan, D.; Annuk, A. More electric aircraft challenges: A study on 270 V/90 V interleaved bidirectional DC–DC converter. *Energy Rep.* **2022**, *8*, 1133–1140. <https://doi.org/10.1016/j.egy.2022.06.084>.
9. Alex, Y.; Divakaran, N.; Srinivasan, P.; Uthappa, U.T.; Mubarak, S.; Al-Harhi, M.; Dhamodharan, D. Advancing Sustainable Energy through Battery Repurposing and Micro Recycling. *J. Energy Storage* **2026**, *141*, 119317. <https://doi.org/10.1016/j.est.2025.119317>.
10. Lai, X.; Huang, Y.; Deng, C.; Gu, H.; Han, X.; Zheng, Y.; Ouyang, M. Sorting, Regrouping, and Echelon Utilization of Large-Scale Retired Lithium Batteries: A Critical Review. *Renew. Sustain. Energy Rev.* **2021**, *146*, 111162. <https://doi.org/10.1016/j.rser.2021.111162>.
11. Siddanth, S.G.; Manna, U.; Saquib, M.; Selvakumar, M.; Nayak, R. Machine Learning–Driven Prediction and Analysis of Lifetime and Electrochemical Parameters in Graphite/LFP Batteries. *Ionics* **2025**, *31*, 12901–12918. <https://doi.org/10.1007/s11581-025-06751-x>.
12. Schuster, S.F.; Brand, M.J.; Berg, P.; Gleissenberger, M.; Jossen, A. Lithium-Ion Cell-to-Cell Variation during Battery Electric Vehicle Operation. *J. Power Sources* **2015**, *297*, 242–251. <https://doi.org/10.1016/j.jpowsour.2015.08.001>.
13. U.S. Department of Energy. *Battery Test Manual for Electric Drive Vehicles. Rev3*; Idaho National Laboratory: Idaho Falls, ID, USA, 2015.
14. Waag, W.; Sauer, D.U. Adaptive estimation of the electromotive force of the lithium-ion battery after short relaxation times for online applications. *J. Power Sources* **2013**, *240*, 243–252. <https://doi.org/10.1016/j.apenergy.2013.05.001>.
15. Andrea, D. *Battery Management Systems for Large Lithium Ion Battery Packs*; Artech House: Houston, TX, USA, 2010.
16. Beck, D.; Dechent, P.; Junker, M.; Sauer, D.U.; Dubarry, M. Inhomogeneities and Cell-to-Cell Variations in Lithium-Ion Batteries: A Review. *Energies* **2021**, *14*, 3276. <https://doi.org/10.3390/en14113276>.
17. Nawaz, M.; Ahmed, J.; Abbas, G. Energy-efficient battery management system for healthcare devices. *J. Energy Storage* **2022**, *51*, 104358. <https://doi.org/10.1016/j.est.2022.104358>.
18. Le, R. Overview of ANSI/CAN/UL 1974:2023—Evaluation for Repurposing or Remanufacturing Batteries. UL Solutions Presentation. 2024. Available online: <https://studylib.net/doc/28368415/overview-of-ansi-ul-1974-2023-202405-v1> (accessed on 5 July 2026).

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.