

Original Article

SECOND LIFE ASSESSMENT OF SALVAGED 18650 LITHIUM-ION CELLS USING CAPACITY AND INTERNAL RESISTANCE METRICS

Linus Kweku Labik^{1,2,*} , Felix Asirifi Asare¹ , Daniel Junior Awuku Larbi² , Bright Senyo Freeman² , Nicholas Blepo Tetteh¹ , and Wilhelmina Sharon Jones¹ 

¹AstroXMat Research Laboratory, Department of Physics, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.

²Department of Physics, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana.

*Corresponding author, E-mail: linusk.labik@knust.edu.gh (Tel.: +233-262326483)

ABSTRACT

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The increasing waste stream of end-of-first-life lithium-ion batteries poses an important challenge and a circular economy opportunity via second-life applications. Nonetheless, trusted characterisation strategies are critical for confirming the safety and functionality of repurposed cells. This study analyses the viability of 18650 cells salvaged from laptop, power tool, and electric vehicle (EV) battery packs according to a dual-parameter framework based on residual capacity (State of Health, SoH) and DC internal resistance (DCIR). Measured SoH ranged from 50.0% to 98.0%, and DCIR ranged from 90 to 500 mΩ across the 22 characterised cells. This is, to our knowledge, among the first studies to combine dual-parameter screening with an explicit threshold sensitivity analysis across three distinct salvaged cell chemistries. Although 77.3% of the 22 characterised cells continued to possess a SoH $\geq 70\%$, only one cell (4.5%) passed a conservative reuse threshold in which both SoH $\geq 70\%$ and the direct current internal resistance (DCIR) were $< 100 \text{ m}\Omega$. SoH showed a strong inverse correlation with DCIR (Pearson $r = -0.76$, $R^2 = 0.57$). Cells from the EV system showed maximum SoH retention with fair DCIR readings. The findings show that internal resistance, rather than capacity fade alone, is a key limiting factor to second-life applicability for power-demanding uses and highlight the need for multi-parameter screening protocols including resistance to reduce risks of unwanted low-performing battery reuse.

Keywords: Lithium-Ion Batteries, Second-Life, State of Health (SoH), Internal Resistance, Battery Degradation.

1. INTRODUCTION

Li-ion batteries (LIBs) are widely used in transport and portable electronic applications because they have long cycle life, high energy density, and a low self-discharge rate (Stanchev & Hinov, 2025). Due to their vast applications, the volume of LIBs reaching their end-of-first-life (EoL1) has increased drastically. For example, in an electric vehicle, a battery reaches its EoL1 when the ratio of its current capacity to its nominal capacity (expressed as a percentage) reduces significantly to a range of 70% to 80%. This percentage is termed the battery's State of Health (Patel *et al.*, 2024). This does not mean that the battery is electrochemically exhausted since it retains a great fraction of its original energy storage capacity. With this information, it can be said that lithium-ion cells enclosed in consumer electronics, portable power tools, and retired electric vehicles discarded annually still have some residual capacity in them that can be used for second-life applications (Salinas *et al.*, 2019).

A report by Christensen *et al.* (2021) stated that when LIBs are disposed of improperly, they lead to severe environmental and safety hazards. These include chemical leakages that are toxic and also thermal runaway events in landfills. To prevent this, recycling must be intentionally applied, but since it is energy-intensive, it faces a lot of economic and logistical challenges, especially in collection and cell chemistry classification. After recovery or recycling, a concept of "second-life" comes up within a circular economy framework (Nazim & Madurai Elavarasan, 2026). It involves using the EoL1 batteries for

less demanding roles, especially stationary energy storage, backup power systems, and low-speed electric vehicles (Akram & Abdul-Kader, 2024). This makes the stress of recycling worthwhile as it defers costs and protects the environment. A central challenge for both science and engineering is how used lithium-ion cells are evaluated and categorised. Reliable second-life assessment depends on accurate estimation of battery health states such as state of health, state of power, and degradation behaviour (Lin *et al.*, 2019). The deterioration of these batteries results from internal (chemical) and physical processes such as the formation and thickening of the solid electrolyte interphase (SEI), loss of lithium inventory, degradation of the active materials, and electrolyte breakdown (Birkel *et al.*, 2017). Loss of active lithium inventory directly reduces the cell's available capacity, seen as SoH decline, while SEI growth impedes ionic transport across the electrode-electrolyte interface, seen as a rise in internal resistance. Degradation proceeds differently across the three chemistries evaluated here: LCO (laptop) cells are more prone to cathode dissolution and electrolyte oxidation at high voltage, LMO (drill) cells to manganese dissolution, and NMC (EV) cells generally show slower capacity fade under moderate cycling, consistent with the source-dependent SoH and DCIR spreads reported in Section 3.

All these processes show a significant change in two externally measurable parameters, namely the internal resistance (IR) and the capacity (SoH). An increase in IR leads to greater ohmic losses, load heat generation, and low power capability. These accelerate

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degradation and elevate safety risks (Mandli *et al.*, 2019). A work by Pillai *et al.* (2025) highlighted the importance of accurate internal resistance estimation if we want LIB health assessment to be reliable. Furthermore, comprehensive assessment procedures for evaluating retired EV batteries that are used for repurposing or second-life duties have been developed. This emphasises the technical, economic, and even safety regulations of the batteries (Montes *et al.*, 2022); however, comparative studies that combine practical screening parameters such as SoH and internal resistance are less common in the literature. This gap is addressed here by applying a combined SoH–DCIR screening protocol across three distinct salvaged cell chemistries within a single framework, extended by an explicit threshold sensitivity analysis, to our knowledge a novel combination for this application. SoH and DCIR were selected as the two evaluation criteria because they are directly measurable with low-cost equipment while capturing, respectively, energy fade and power fade; the specific thresholds applied (SoH $\geq 70\%$, DCIR < 100 m Ω) are introduced in Section 2.

This study addresses this gap by conducting an investigation of the potential of 18650 cells that have been recovered from three different sources. A practical method for measuring critical battery health parameters, namely the State of Health and Internal Resistance, is used. The primary objectives are to determine the number of cells that will meet the defined performance thresholds for reuse, analyse the correlation between capacity fade and resistance rise, evaluate how sensitive this classification is to the chosen resistance threshold, and analyse whether capacity alone is sufficient for classifying cells for second-life reuse.

2. MATERIALS AND METHODS

Cell Salvage and Sources

A total of thirty-one cells were recovered from the types of retired battery packs listed above. The first group consisted of laptop battery packs from different manufacturers. They had Lithium Cobalt Oxide chemistry and nominal capacities of 2200 mAh. The second group was also obtained from a 14.4 V cordless drill battery pack and had Lithium Manganese Oxide cells with nominal capacities of 1500 mAh. For the third group, a module was taken from an electric vehicle battery system. It consisted of nickel-manganese-cobalt cells with nominal capacities of 2500 mAh. The cell chemistries were identified from manufacturer pack labelling and datasheet cross-reference rather than confirmed by direct elemental or spectroscopic analysis; this is noted as a limitation in Section 4. These three sources were selected to represent common second-life sourcing streams (household electronics, power tools, and automotive modules) because they span between distinct chemistries and duty cycles. The packs were opened in a laboratory using insulated gloves and lab coats. Some cells had visible defects like dented casings and broken terminals, so they were removed and not tested further. After this step and the OCV screening discussed in the next section, twenty-two cells were left for characterisation. For easy identification, all the cells were labelled. Laptop cells were labelled L1 to L13, drill cells D1 to D4, and EV cells EV1 to EV5. All cells were obtained through e-waste collection channels in line with responsible recovery practices and circular economy considerations (Islam & Iyer-Raniga, 2022).

Initial Screening

Of the thirty-one recovered cells, nine were excluded during visual inspection (four for case swelling, four for terminal corrosion, and one for physical deformation); no further cells were excluded by OCV screening, as all twenty-two remaining cells returned an OCV above the 2.5 V threshold described below. After the visual screening, the open-circuit voltage of the cells was measured using a digital multimeter with a threshold of 2.5 V as the minimum. This threshold was applied because it tells us about electrochemical risks, especially those in the cobalt-based laptop cells, where a deep discharge can trigger copper collector dissolution in the anode. Such dissolution may lead to issues like internal short circuits upon recharge, representing an irreversible and hazardous failure mode (Langner *et al.*, 2021). OCV alone provides only a coarse safety screen and does not resolve resistance or usable capacity; cells with acceptable OCV can still fail on SoH or DCIR grounds, as shown in Section 3.

Charging Protocol

All cells were charged under controlled conditions before testing, with individual charging done with TP4056 single-cell lithium-ion charger modules that use constant current constant voltage method (Kok *et al.*, 2024). Each cell was first charged at a constant current until the voltage reached 4.20 V, after which the voltage was held constant with the current decreasing gradually. A charging current of 0.5 A was used for all the cells. This value was selected to limit thermal stress of the cells while allowing a reasonable charging time. During charging, voltage and temperature were monitored continuously. No unusual temperature rises or voltage behaviour was observed. All charging was performed at 25°C. No independent verification of the cutoff voltage was performed against an external calibrated reference, given the TP4056 modules' manufacturer-specified tolerance of approximately $\pm 1\%$ (≈ 0.042 V at the 4.20 V cutoff). Because all cells were charged on the same hardware type under the same protocol, this tolerance is expected to act as a systematic rather than a random source of error; its precise propagation into reported SoH values was not separately quantified. This same procedure was applied to all samples despite the fact that the cell conditions and chemistry vary to keep the process consistent, making it easier to compare results obtained during discharge and resistance measurements across the different cells.

Discharge Testing and Capacity Measurement

Each cell was allowed to rest for 1 hour after charging without performing any additional measurements. This meant that the voltage could stabilise and minimise the influence of a transient relaxation. Discharge tests were performed in the study using a programmable USB electronic load tester that was set at a constant current of 0.5 A. A cutoff voltage of 2.50 V was also used here to avoid deep discharge conditions that can damage the cell. The State of Health was calculated as the ratio of the measured discharge capacity to the nominal capacity and expressed as a percentage (Fan *et al.*, 2023) according to Equation (1):

$$\text{SoH (\%)} = \frac{C_{\text{measured}}}{C_{\text{nominal}}} \times 100\% \quad (1)$$

For all experiments, a discharge current of 0.5 A was utilised so that safe and consistent conditions during testing between all batteries would be ensured. Increased current can accentuate differences in internal resistance and power behaviour and also lead to increased heat and strain on the cells.

Internal Resistance Estimation

The DC internal resistance method, which estimates ohmic losses from the voltage drop at the start of discharge, was used for the internal resistance estimation (Schweiger *et al.*, 2010). For the cell voltage to be close to open circuit conditions at the start of the 0.5 A discharge, the measurements were taken after one hour. The voltage was recorded at one second, denoted as $V_{t=1s}$. This follows the general voltage-drop principle underlying DCIR estimation, formalised in Equation (2) (Tian *et al.*, 2022):

$$R_{\text{DCIR}} \text{ (m}\Omega\text{)} = \frac{V_{\text{OCV}} - V_{t=1s}}{I_{\text{dis}}} \quad (2)$$

where V_{OCV} is the open circuit voltage measured before discharge, and I_{dis} is the discharge current set at 0.5 A. Equation (2) states the general estimation principle; the DCIR values reported in Table 1 were read directly from the load tester's onboard resistance function, which applies its own internal pulse current and timing distinct from the 0.5 A / 1 s parameters used for the OCV and $V_{t=1s}$ columns reported for reference, and do not reproduce exactly via Equation (2) from those two columns alone. This is noted explicitly to avoid the appearance of an inconsistency between the reported voltage columns and the DCIR column in Table 1. This measurement interval was set at one second to limit the impact of diffusion-related polarisation and ensure that the measured value mainly reflects ohmic behaviour. Increased values of DCIR are typically attributed to ageing phenomena including solid electrolyte interphase growth, contact loss in the electrode framework, and electrolyte decomposition that can inhibit ionic/electronic conduction (Barré *et al.*, 2013; Dubarry & Liaw, 2009). DCIR was

utilised as a broad marker here to compare the state of cells and assist with cell screening.

Reusability Criteria

Dual thresholds were used to classify the salvaged cells for second-life utilisation specifically considering energy retention as well as power capability. The first criterion was SoH greater than or equal to 70%, a commonly cited screening threshold for lithium-ion batteries in automotive and stationary applications, though the practical end-of-life point varies by application and manufacturer requirements (Blomgren, 2017). At this level, cells still have a majority of their usable energy remaining and are still capable of lower-demand applications (Neubauer & Pesaran, 2011). This remains a substantial capacity, but EV packs are often retired around this range. The second criterion was a DC internal resistance of less than 100 mΩ, chosen to limit both voltage drop and heating during moderate current operation. The 100 mΩ threshold for reuse was conservative simply because new 18650 cells' internal resistances tend to range between 30 mΩ and 80 mΩ (Patel *et al.*, 2024). Higher internal resistance is generally associated with ageing effects such as SEI layer growth and loss of electrode contact, which reduce both performance and safety (Salinas *et al.*, 2019). Cells meeting both conditions were classified as reusable, while those that failed either criterion were assigned for recycling. This unified threshold is a simplification for high-power chemistries such as the drill cells, whose new-cell nominal DCIR is markedly lower than that of the laptop/EV cells evaluated here; a DCIR threshold sensitivity analysis (Section 3, Table 2) was therefore performed to test this directly.

The methodology of this work is summarised in Figure 1 below.

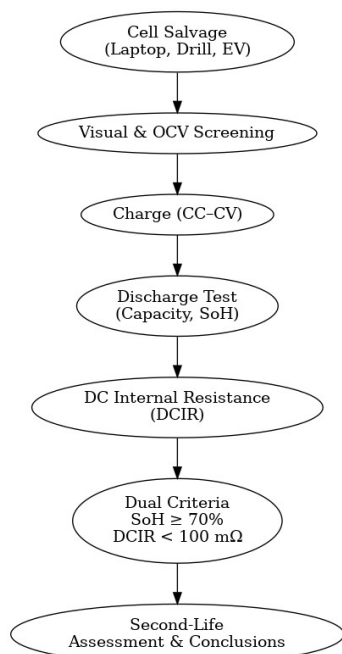


Figure 1: Simplified workflow of experimental methodology.

3. RESULTS

Initial Screening

Visual inspection and open-circuit voltage (OCV) screening were performed first. Of the thirty-one recovered cells, nine were excluded

during visual inspection (four for case swelling, four for terminal corrosion, and one for physical deformation) and were excluded from further experimental testing on safety grounds; no additional cells were excluded on OCV grounds alone, as all twenty-two remaining cells returned an OCV above the 2.50 V threshold. For instance, cells below or even at this voltage limit are known to have undergone several negative electrochemical changes. Copper dissolution from the current collector can be initiated in deeply discharged cells, leading to the migration of the copper ions as well as their subsequent deposition within the electrode structure. This can lead to the growth of metallic dendrites that pierce the separator, create internal short circuits, and lead to dangerous failure modes (Guo *et al.*, 2016; Zhang, 2006). For the visibly defective cells, they either had swelled, had their terminals corroded, or had their case deformed. These can also be symptoms of gas generation and breakdown of electrolyte (Maddipati *et al.*, 2025). In cells made of cobalt, over-discharging accelerates transition-metal oxide reduction, cathode lattice destabilisation, and gaseous by-product production (Luo *et al.*, 2022). In manganese, deep discharge can exacerbate Jahn–Teller distortions in the spinel structure that compromise mechanical integrity.

The exclusion of these nine cells led to a final dataset of twenty-two cells that showed no visible defects or low-OCV risk indicators and were suitable for further characterisation. The complete dataset reported OCV, loaded voltages, the DCIR values obtained, measured capacities, derived SoH, and classification outcomes, as presented in Table 1.

The complete discharge voltage-time trace was not retained for every cell in the cohort, and in particular for cells L3 and L10; their reported capacity and SoH values (Table 1) were recorded directly from the discharge test at the time of measurement and are unaffected.

State of Health Distribution

The State-of-Health values that were measured ranged from 50.0% to 98.0%. The lowest was from a weak laptop cell while the highest was from a strong EV-module cell (EV4). After applying the SoH criterion, seventeen cells (77.3% of the cohort) qualified. The distribution by source can be seen in Table 1 and Figure 2. It can be seen that the laptop cells had the widest spread, while the drill cells clustered closely. This pattern is consistent with a power-oriented duty cycle typically associated with cordless-drill applications, though this was not independently verified. Taking the cells from the EV module, they showed the highest and most consistent retention with an average of 86.4%. All this information shows that chemistry type and purpose of application are important in second-life potential.

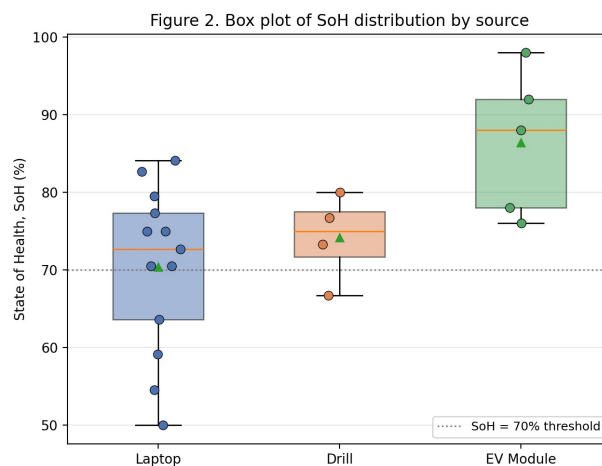


Figure 2: Box plot of SoH distribution by source.

Table 1: Test Results for the 22 characterised 18650 cells.

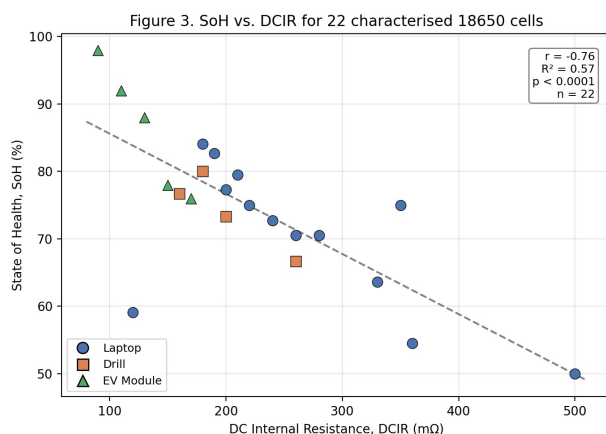
Cell ID	Source	OCV (V)	$V_{t=1s}$ @0.5 A (V)	DCIR (mΩ)	Capacity (Ah)	Energy (Wh)	SoH (%)	Status
L1	Laptop	3.92	3.82	200	1.70	6.2	77.3	Reject
L2	Laptop	3.88	3.74	280	1.55	5.5	70.5	Reject
L3	Laptop	3.95	3.70	500	1.10	3.9	50.0	Reject
L4	Laptop	3.91	3.78	240	1.60	5.7	72.7	Reject
L5	Laptop	3.87	3.65	350	1.65	5.8	75.0	Reject
L6	Laptop	3.90	3.85	120	1.30	4.7	59.1	Reject
L7	Laptop	3.89	3.79	210	1.75	6.2	79.5	Reject
L8	Laptop	3.93	3.81	190	1.82	6.5	82.7	Reject
L9	Laptop	3.86	3.62	330	1.40	4.9	63.6	Reject
L10	Laptop	3.94	3.83	180	1.85	6.6	84.1	Reject
L11	Laptop	3.90	3.75	260	1.55	5.4	70.5	Reject
L12	Laptop	3.92	3.80	220	1.65	5.9	75.0	Reject
L13	Laptop	3.91	3.70	360	1.20	4.3	54.5	Reject
D1	Drill	3.93	3.83	160	1.15	4.1	76.7	Reject
D2	Drill	3.90	3.79	200	1.10	3.9	73.3	Reject
D3	Drill	3.88	3.72	260	1.00	3.6	66.7	Reject
D4	Drill	3.92	3.82	180	1.20	4.3	80.0	Reject
EV1	EV Module	3.97	3.90	110	2.30	8.0	92.0	Reject
EV2	EV Module	3.96	3.88	130	2.20	7.6	88.0	Reject
EV3	EV Module	3.95	3.85	150	1.95	6.8	78.0	Reject
EV4	EV Module	3.94	3.89	90	2.45	8.4	98.0	Reusable
EV5	EV Module	3.96	3.86	170	1.90	6.6	76.0	Reject

Internal Resistance (DCIR) Analysis

From Table 1, it can be seen that the DCIR values ranged from 90 mΩ to 500 mΩ. Most of the cells with lower SoH showed higher DCIR. Since a strict IR criterion of less than 100 mΩ was set, only EV4 met the predefined dual screening criteria. Not even one cell from the many laptop cells passed the dual criteria despite the fact that they passed the capacity check. With this, it was concluded that capacity alone cannot guarantee good functional performance.

Correlation Between SoH and DCIR

In this section, a relationship between capacity fade and resistance rise was determined: a negative correlation with Pearson's $r = -0.76$ and $R^2 = 0.57$ was found, as seen in Figure 3 ($p < 0.0001$, 95% CI $[-0.89, -0.49]$, $n = 22$). With this statistical relationship, we noted that as cells continue to lose active lithium and experience SEI growth, resistance increases due to the progressive degradation of their ionic and electronic pathways. $R^2 = 0.57$ indicates that resistance rise accounts for just over half of the variance in SoH across the cohort; the remaining variance reflects degradation pathways not fully captured by either parameter alone, which is why dual-parameter rather than single-parameter screening is used here. Some cells depart from the overall trend (e.g., L6, with SoH 59.1% but a comparatively low DCIR of 120 mΩ), consistent with the $R^2 = 0.57$ indicating that resistance and capacity fade are correlated but not fully coupled at the individual-cell level.

**Figure 3:** Scatter plot of DC Internal Resistance (DCIR) versus State of Health (SoH).

DCIR Threshold Sensitivity Analysis

Because reuse classification depends heavily on the chosen DCIR threshold, the number of cells passing both the $\text{SoH} \geq 70\%$ and DCIR criteria was recalculated across a range of thresholds (Table 2). Raising the cut-off from 100 mΩ to 150 mΩ triples the pass rate (1 to 3 cells), and a threshold of 200 mΩ, still conservative relative to some stationary-storage screening criteria (Neubauer *et al.*, 2015), admits nine cells (40.9%). This shows that the low overall reuse rate reported here is driven substantially by the choice of a single fixed threshold applied uniformly across chemistries, and that threshold selection should be matched to the power demand of the intended second-life application.

Table 2: Sensitivity of dual-criterion pass rate to the DCIR threshold.

DCIR threshold (mΩ)	Cells passing $\text{SoH} \geq 70\%$ AND DCIR criterion	% of cohort ($n = 22$)
< 80	0	0.0%
< 100 (as used in this study)	1 (EV4)	4.5%
< 120	2 (EV1, EV4)	9.1%
< 150	3 (EV1, EV2, EV4)	13.6%
< 200	9 (L8, L10, D1, D4, EV1, EV2, EV3, EV4, EV5)	40.9%

Reusability Classification

With our criteria, only EV4 passed. This represents 4.5% of the cohort. A sequential filtering is illustrated in Figure 4 to show how the cells were grouped.

Proof-of-Concept Demonstration

Three cells from the cohort were selected to demonstrate why capacity alone is not sufficient for the second-life classification. EV4 ($\text{SoH} = 98.0\%$, $\text{DCIR} = 90 \text{ mΩ}$) was selected since it passed both reuse criteria. L10 ($\text{SoH} = 84.1\%$, $\text{DCIR} = 180 \text{ mΩ}$) was selected because it passed the SoH criterion only and L3 ($\text{SoH} = 50.0\%$, $\text{DCIR} = 500 \text{ mΩ}$) was chosen because it failed both criteria. Being placed under similar loading conditions, EV4 showed the smallest initial voltage drop, moving from 3.94 V to 3.89 V, while L10 and L3 dropped from 3.94 V to 3.83 V and 3.95 V to 3.70 V respectively. Based on their measured capacities, the estimated discharge durations at 0.5 A were approximately 4.9 h for EV4, 3.7 h for L10, and 2.2 h for L3. The complete discharge voltage-time trace for L3 and L10 specifically was not retained; their behaviour here is illustrated via measured voltage

endpoints (Figure 5) rather than a continuous trace, and their capacity/SoH values (Table 1) were recorded directly at the time of testing. This comparison shows that a cell may retain acceptable capacity while still exhibiting poor load performance because of elevated internal resistance. The result therefore supports the use of dual-parameter screening rather than capacity alone when assessing second-life suitability.

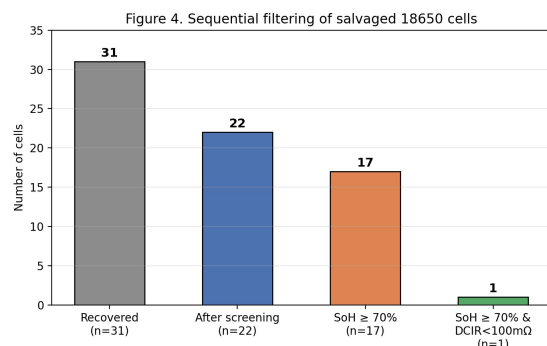


Figure 4: Sequential filtering of salvaged 18650 cells.

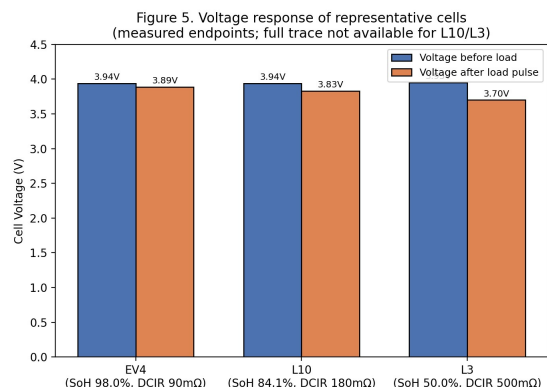


Figure 5: Measured voltage endpoints (before/after load) and capacity of three representative cells with different SoH and DCIR values.

4. DISCUSSION

Interpretation of Key Findings

The key result of this study is the important influence of internal resistance as a disqualifying parameter for second-life use in power applications. This resulted in 77.3% of cells passing the capacity-based SoH criterion, but only 4.5% passing when a combined capacity and resistance criterion was deployed, highlighting a possible omission in second-life considerations that focus simply on residual capacity. The inverse correspondence of $R^2 = 0.57$ between SoH and DCIR is consistent with the coupled electrochemical degradation mechanisms reported in the literature: loss of lithium inventory (causing a capacity fade), active material degradation (capacity loss), and an increase in resistance due to SEI growth/contact loss phenomena. This is probably because the EV module cells are operated within a managed battery system with strict thermal and state-of-charge boundaries, which reduce degradation stress (Keil & Jossen, 2015). The dual-parameter health landscape in Figure 6 synthesises the combined influence of residual capacity and internal resistance on second-life suitability. This representation shows that even if many cells can be classified as viable with respect to capacity only, the acceptable reuse space collapses when considering internal resistance. EV-module cells preferentially occupy the high-SoH, low-resistance region while laptop and drill cells are primarily pushed towards higher resistance values, making them unsuitable for power-demanding second-life applications (by source: laptop mean SoH 70.3%, mean DCIR 264.6 mΩ; drill mean SoH 74.2%, mean DCIR 200 mΩ; EV mean SoH 86.4%, mean DCIR 130 mΩ; individ-

ually, EV DCIR spans 90–170 mΩ and only EV4 clears the 100 mΩ threshold).

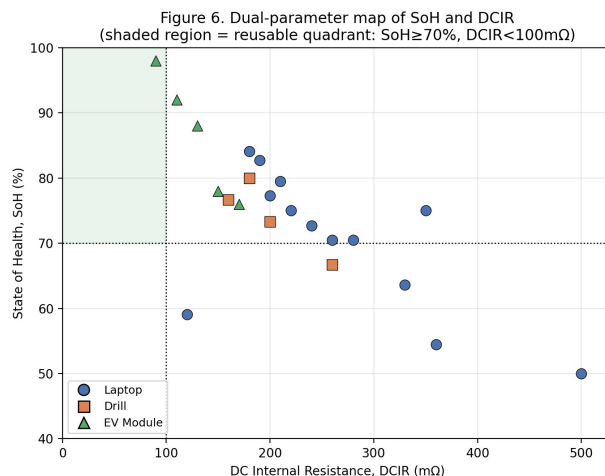


Figure 6: Dual-parameter map of State of Health (SoH) and DC internal resistance (DCIR).

Comparison with Prior Literature

Our recovery rate on capacity (SoH ≥ 70%) of 77.3% was comparable with other studies, for example, a work by Salinas *et al.* (2019), which had a high fraction of laptop cells that maintained more than 70% remaining capacity. George *et al.* (2023), characterising 18650 cells recovered from consumer electronics in Lagos, Nigeria for stationary storage reuse, similarly found a substantial fraction of salvaged consumer-electronics cells suitable for repurposing on capacity grounds. But the near-universal failure on the IR criterion tells a more conservative story. This could be due to non-uniform IR thresholds. Industry screening for stationary storage may allow for higher IR, e.g., < 250 mΩ than the value required of a mobile or power-tool application (Neubauer *et al.*, 2015). Our applied threshold may be conservative for these cells, but this was intentional, to screen for cells suitable for high-power reuse. Wheeler *et al.* (2025), in a long-term ageing study of 18650 cells across first and second life, similarly note that capacity-only projections understate the role of resistance-driven power fade, consistent with the present findings.

Implications for Second-Life Applications

The results found in this work have direct implications for second-life systems design. The cells need to be assessed to make sure they are viable as well as meet the specific requirements of what they will be used for. In low-power applications such as the lighting of LEDs and small consumer devices, cells that have only the IR threshold exceeded can be used, but for high-performance applications, they require cells that have large capacity and low resistance. This tiered approach to application matching is consistent with existing second-life suitability assessment frameworks (Montes *et al.*, 2022).

The origin of cells is also a major factor in cell quality. EV battery modules are designed for longevity and managed by sophisticated BMS, as compared to other heterogeneous consumer electronics waste. Their consistent performance may reflect both chemistry (NMC cathodes with stable lattice structures) and system-level management, though prior usage history could not be separated from these factors in this study. Lastly, the increased prevalence of high resistance demonstrated in this study highlights the importance of thermal safety considerations in second-life deployment. Localised heating can occur within cells as a result of excessive IR, with this heating accelerating degradation and increasing the likelihood of thermal runaway. Because resistive heating scales with the square of current ($P = I^2 R$), even a moderate DCIR increase can produce disproportionate heating under the higher pulse currents typical of power-tool or fast-charge use, relative to the low 0.5 A screening current used here. Thus, any second-life deployment must incorporate protective

measures such as a matched BMS, appropriate fusing, and thermal monitoring (Feng et al., 2018).

Limitations of the Study

The major limitation of this study is the sample size. The sample, though small ($n = 22$), was informative. Also, the use of the DCIR method at a fixed current and short timescale was insufficient for revealing the full frequency-dependent impedance response obtainable specifically via electrochemical impedance spectroscopy (EIS). This was a limitation, as EIS would have allowed for further insights (Fan et al., 2023). The second-life application was also not tested for cycle life. The long-term ageing trajectory of these cells is also unknown, including whether there might be a “knee point” where their degradation accelerates. The study did not evaluate self-discharge rate, another important metric of health.

A uniform 0.5 A discharge/charge current was applied across all three chemistries, representing a low C-rate ($\sim 0.2\text{--}0.3C$) for the drill and EV cells relative to the laptop cells, and may understate resistance-driven degradation for the higher-power-rated chemistries under realistic loads.

Cell chemistries were assigned from manufacturer labelling rather than confirmed by direct compositional analysis, as noted in Section 2.

Each cell was tested once; repeat measurements were not performed, so measurement repeatability and uncertainty were not directly characterised.

All measurements were performed at a fixed ambient temperature (25°C) and a single state of charge (near-full, post-charge); both are known to influence DCIR independently of ageing state (Rodrigues et al., 2017), and their effects were not characterised here.

The prior usage and cycling history of the recovered cells was unknown, limiting the extent to which observed degradation can be attributed to chemistry versus first-life duty cycle.

The binary pass/fail structure of the dual-criteria classification is itself a simplification, treating a cell just below a threshold the same as one far beyond it; this is discussed further under Future Research.

Future Research Directions

Multiparameter sorting algorithms that include capacity, DCIR, EIS data, and self-discharge measurements should be available so that predicting remaining useful life with great accuracy will be easier. In solar energy storage applications too, an extended cycle life test would provide good models of capacity fading as well as reliable warranties. Customised charging cycles or pulse conditioning could be investigated as a potential approach to lowering internal resistance in slightly compromised cells, though this was not tested in the present study. Liu and Wang (2024) found that a pulse charge–discharge pattern reduced average internal resistance by approximately 17.5% and increased capacity retention by 3.76% over 800 cycles relative to a CC-CV baseline, supporting pulse conditioning as a promising direction for second-life cells specifically. A continuous or tiered suitability score, in place of the binary threshold used here, and long-term validation of the screening protocol under real operating conditions, are also recommended.

5. CONCLUSION

This work demonstrates the potential of residual capacity (SoH) and internal resistance (DCIR) as dual diagnostic measures, using physics-informed methodologies, to assess second-life viability in lithium-ion cells. Although a high percentage of cells (77.3%) retained more than 70% of their nominal capacity, the results show that internal resistance should be considered alongside residual capacity before batteries can be reused. Since only one cell (4.5%) could achieve both aspects when a conservative cut-off of 100 m Ω was used, capacity-only screening may fail to identify cells with degraded power capability and elevated resistive losses. The fact that the DCIR and SoH have a strong inverse correlation ($r = -0.76$, $R^2 = 0.57$) is consistent with the coupled electrochemical degradation mechanisms reported in the literature for lithium-ion ageing in the real world. The transition to a circular lithium-ion economy is becoming necessary around the world, and to be successful, we have to

ensure we use active assessment protocols. Our findings demonstrate that resistance-inclusive screening provides greater diagnostic depth than capacity alone and can contribute to safer second-life screening; economic implications were not evaluated in this study. By applying this methodology, a responsible second-life ecosystem where battery reliability is quantified can be supported. This study provides a practical framework for evaluating second-life lithium-ion cells, particularly in resource-constrained environments where low-cost diagnostic methods are essential.

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The authors have no conflict of interest to declare concerning the publication of this paper.

Author Contributions:

Conceptualisation, study design, manuscript writing, and supervision: L.K.L. Proof-of-concept assembly, practical demonstration, and manuscript writing: F.A.A. Cell salvage, visual inspection, and initial screening: D.J.A.L. Charging protocol, discharge testing, and capacity measurement: B.S.F. Internal resistance measurement and statistical evaluation: N.B.T. Data analysis: W.S.J. All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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