BATTERY CIRCULARITY NEEDS A COMMON LANGUAGE

A Framework for Verifiable State of Health and Application-Specific Remaining Useful Life

WHITE PAPER

TECHNICAL WHITE PAPER - DRAFT FOR REVIEW

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Core proposition

Battery qualification should combine provenance, first-life and storage history, present non-destructive diagnostics, and the requirements of the proposed next application. The output should be a multidimensional health state, application suitability, application-specific RUL, and an explicit confidence level.

Review status

BCQF is a proposed technical framework intended for discussion, experimental validation and peer review. It is not an adopted industry standard, certification procedure or safety qualification method. Please do not cite this review draft as a final publication.

Executive Summary

The transition to electric mobility will create a large population of batteries that have reached the end of their first application while retaining useful electrochemical capability. Circularity requires a defensible way to decide whether a battery should continue in service, be repaired or remanufactured, be repurposed, or proceed to material recovery.

Current regulation and standards already move in this direction. The EU Battery Regulation requires BMS access to state-of-health and expected-lifetime parameters for purposes including residual-value assessment and repurposing. UNECE GTR No. 22 addresses in-vehicle battery durability for light-duty electrified vehicles, and GTR No. 25 extends the durability framework to electrified heavy-duty vehicles. UL 1974 addresses sorting and grading for repurposing, while IEEE 2993-2025 addresses design of energy-storage systems using second-life EV batteries.

The remaining technical gap is not simply another SOH algorithm. It is an interoperable evidence framework connecting what a battery was at birth, how it was integrated, what it experienced, how it behaves now, and what the next application will demand.

The proposed Battery Circularity Qualification Framework (BCQF) produces four outputs:

$$BCQF = \{ H, S_A, RUL_A, C \}$$

H	Multidimensional battery health state
S_A	Suitability for proposed application A
RUL_A	Remaining useful life under application A
C	Confidence in the assessment

The framework deliberately avoids collapsing all battery condition into one universal SOH percentage. A battery can be unsuitable for a high-power traction duty yet remain useful for a lower-C-rate stationary application. RUL is therefore conditional on future duty and the end-of-life criterion of the proposed application.

1. The Circularity Decision

A traction battery reaching the end of automotive service does not necessarily reach the end of useful life. OEM end-of-life criteria describe suitability for the original application, not necessarily the physical end of the battery.

$$EOL_{Application\ 1} \mathrel{!}= EOL_{Battery}$$

The circularity question should therefore be: **Based on provenance, available lifecycle history, present measurable condition and the requirements of the proposed next application, what can this battery safely and reliably do next, for approximately how long, and with what level of confidence?**

2. Why SOH Should Not Be a Single Number

Capacity- or energy-retention metrics remain useful reference indicators, but ageing also manifests through resistance growth, declining power capability, altered thermal response, self-discharge and cell-to-cell inconsistency. Recent second-life literature highlights uncertainty arising from incomplete first-life history, non-uniform degradation, chemistry variation and OEM-specific charging protocols [1].

$$SOH_E = E_{measured} / E_{reference}$$

For circularity, the health state should therefore be represented as a vector rather than an opaque scalar.

3. RUL Is Application-Specific

RUL is not an intrinsic property of a battery. Future degradation depends on SOC window, depth of discharge, C-rate, temperature, throughput, calendar time and thermal management. Research on end-of-life battery systems explicitly considers RUL under different second-life applications [2].

$$RUL_A = P(T_{EOL,A} \mid H_{life}, H_{current}, D_A, EOL_A)$$

A meaningful RUL statement must therefore declare the future duty profile and the application-specific EOL criterion, and should report uncertainty rather than a falsely precise single number.

4. Lifecycle Evidence Chain

Qualification should begin with evidence created at manufacture, not when the battery is removed from a vehicle. The proposed chain is:

Cell birth data -> Pack/OEM data -> First-life history -> Storage/transport -> Current diagnostics -> Second-life duty

5. Layer 1 - Cell Manufacturer Reference Data

The cell manufacturer should provide a standardized baseline: chemistry and format; nominal and minimum capacity; nominal energy; initial resistance/impedance under defined conditions; charge/discharge limits; voltage and temperature limits; recommended SOC range; cycle-life and calendar-ageing characterization; fast-charge constraints; safety limits; and relevant batch information.

Commercially sensitive characterization need not be public. Standardized derived reference parameters can provide a reliable **birth reference** against which later condition is assessed.

6. Layer 2 - Pack and OEM Information

The pack or vehicle OEM should provide pack topology, gross and usable energy, SOC buffers, thermal strategy, charge/discharge power limits, derating logic, balancing strategy, BMS protection thresholds, certified energy where applicable, configuration information, warranty thresholds and first-life EOL criteria.

This layer separates the electrochemical capability of the cells from the capability made available in the original product.

7. Layer 3 - First-Life Operational History

Where available, standardized lifecycle data should include calendar age, operating hours, charged and discharged energy, equivalent full cycles, depth-of-discharge distribution, SOC and temperature histograms, combined SOC-temperature exposure, fast-charge exposure, peak currents, thermal excursions, low-temperature charging, deep discharge, cell-voltage and temperature dispersion, balancing activity, isolation faults and relevant BMS safety events.

Energy throughput can support an EFC calculation, but throughput alone cannot represent degradation.

8. Layer 4 - Storage and Logistics History

Ageing continues after removal from service. Storage duration, SOC, temperature history, prolonged high-SOC exposure, deep discharge, maintenance charging, environmental exposure and logistics incidents should therefore remain part of the evidence chain.

9. Why Exhaustive Cell Testing Is Not Scalable

A traction battery can contain hundreds or thousands of cells. Complete disassembly and individual characterization is operationally expensive and may introduce additional handling risk; destructive characterization is incompatible with returning a cell to service. UL's repurposing guidance also recognizes the role of non-destructive electrical testing, visual examination and battery information [3].

The proposed principle is: **use multiple independent indicators to identify where health or safety cannot be established with adequate confidence, and escalate testing selectively.**

10. Three-Stage Qualification Method

Stage 1 - Historical screening. Analyse provenance, throughput, thermal/SOC exposure, fast charging, abnormal events, diagnostics, storage history, and data completeness. Severe events can trigger rejection or mandatory investigation independently of estimated SOH.

Stage 2 - Non-destructive pack diagnostics. Standardized testing should include usable energy/capacity, resistance growth at defined SOC and temperature, pulse power, cell-voltage dispersion, thermal dispersion, voltage relaxation/self-discharge, and electrical safety checks.

Stage 3 - Anomaly-driven investigation. Cells or modules whose electrical, thermal or balancing behaviour materially differs from peers are escalated to deeper inspection or module-level testing. Testing intensity increases only where evidence warrants it.

11. Proposed Battery Health Vector

A candidate representation is:

$$H = [H_E, H_Q, H_P, H_R, H_B, H_T, H_S]$$

where the dimensions represent energy retention, capacity retention, power capability, resistance/impedance condition, cell/module consistency, thermal behaviour and safety/diagnostic condition. The final variables and normalization require peer review and experimental validation.

These dimensions should not be arbitrarily weighted into another universal SOH percentage; their importance changes with the next application.

12. The Second-Life Application Is an Input

Every proposed application should itself have a requirement vector covering energy, power, maximum C-rate, thermal environment, cycling profile, expected lifetime and safety constraints.

$$S_A = f(H, R_A)$$

A battery may therefore fail continued heavy-duty traction requirements but satisfy stationary-storage requirements. Circularity becomes a matching problem between remaining capability and future duty.

13. Application-Specific RUL

For batteries that satisfy initial suitability criteria, a hybrid model can combine manufacturer ageing data, physics-informed degradation models, historical operation, present diagnostics, fleet/population data where available and the proposed future duty.

A useful certificate should report the assumed duty, median predicted life, a prediction interval and the dominant sources of uncertainty.

14. Confidence as a First-Class Output

Two batteries with the same measured energy retention should not receive equally precise assessments if one has authenticated lifecycle data and the other has uncertain provenance and unknown storage history.

Confidence should therefore reflect provenance, data completeness and integrity, measurement uncertainty, model validity for the chemistry, similarity between validation conditions and actual duty, diagnostic coverage and cell/module consistency.

Battery Qualification = Health + Application Suitability + RUL + Confidence

15. Relationship to Regulation and Standards

EU Regulation 2023/1542 already requires up-to-date BMS data for SOH and expected-lifetime parameters and provides read-only access for purposes including residual-value assessment and repurposing. Annex VII includes SOCE for EV batteries and, for other covered batteries, parameters such as remaining capacity, power capability where possible, efficiency, self-discharge and ohmic resistance [4].

UNECE GTR No. 22 provides an in-vehicle battery durability framework for electrified light-duty vehicles; GTR No. 25, issued in February 2026, covers electrified heavy-duty vehicles [5,6]. UL 1974 covers sorting and grading for repurposing, and IEEE 2993-2025 addresses energy-storage-system design using second-life EV batteries [3,7].

BCQF is intended to sit between traceability, safety qualification and application engineering: an interoperable evidence-to-decision layer rather than a replacement for existing standards.

16. Validation and Governance

The framework requires validation across chemistries, manufacturers, cell formats, pack architectures, climates, first-life duties, ageing histories and second-life applications. Blinded inter-laboratory studies should establish reproducibility.

RUL requires prospective validation: predictions made at t0 should be compared with observed life when batteries are subsequently operated under the declared duty until the defined EOL condition.

Governance should include cell and pack manufacturers, OEMs, BMS suppliers, fleet operators, second-life integrators, recyclers, independent laboratories, universities, insurers, financiers, regulators and standards organizations. Proprietary algorithms need not be disclosed, but reported health estimates should be independently verifiable against standardized reference procedures.

17. From Battery Passport to Battery Decision

Battery passports can provide identity, provenance and lifecycle information. Circularity needs the next layer: decision-grade information.

Identity -> Lifecycle evidence -> Current health -> Application requirements -> Suitability -> RUL -> Confidence

A mature circular battery economy should be able to answer not merely whether a battery is above or below an arbitrary SOH threshold, but what it can safely do next, for how long, and with what confidence.

References

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[4] European Parliament and Council. Regulation (EU) 2023/1542 concerning batteries and waste batteries, Article 14 and Annex VII (consolidated text).

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This white paper presents a proposed technical framework for discussion and peer review. The BCQF terminology and structure are proposals and should not be interpreted as an adopted industry standard.

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