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One-Shot, Hybrid Diagnostics Are Essential for Reliable EV Battery End-of-Life Assessment

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Introduction

As electric vehicle (EV) adoption accelerates and regulatory pressure intensifies, determining a battery's end-of-life (EoL) condition has become a critical challenge. This article argues that reliable EoL decisions can only be achieved through one-shot diagnostic methods that combine machine learning (ML) with first-principles electrochemical knowledge, especially given the lack of consistent lifecycle battery data.

Background

The EU Battery Regulation and the upcoming Battery Passport require transparent, traceable, and verifiable information across the entire EV battery lifecycle. In practice, however, such complete longitudinal data almost never exists. Batteries move across owners, geographies, usage profiles, and management systems, resulting in fragmented or missing records.

EV batteries typically reach EoL when their State of Health (SoH) decreases to ~70–80% of original capacity or when damage or safety concerns arise. At this point, stakeholders must decide whether the battery should be recycled or repurposed for second-life applications - decisions that hinge on accurate diagnostics.

Supporting Arguments

Incomplete lifecycle data demands one-shot diagnostics: Since battery history is rarely available or trustworthy, EoL assessments must rely solely on **data captured at the time of inspection**. One-shot approaches - using limited measurements such as impedance or voltage relaxation - are therefore essential.

Hybrid ML + first-principles models improve robustness: Pure ML systems struggle with sparse or inconsistent data. However, **hybrid models grounded in electrochemistry** can infer degradation pathways and capacity loss even when historical data is missing. This approach has been demonstrated in several recent international contributions:

- Tuschkan, Schagerl, Zivadinovic (AABC Europe 2024) showed how **AI-based digital twins** detect anomalies and estimate performance using minimal inputs.
- Follow-up work presented at **JSAE 2024** confirmed these models' ability to adapt across cell formats and usage conditions.
- Didcock & Schagerl (AABC Europe 2025) demonstrated how **AI-powered monitoring** solutions enhance cell/battery assessment in testing environments with incomplete datasets.

- The work presented by Peischl (AIOTI Signature Event 2024) highlighted the broader need for **trustworthy, explainable diagnostics** within digital-twin ecosystems.
- **One-shot hybrid diagnostics support regulatory compliance.** Accurate, auditable SoH estimation enables correct EoL classification even without historical records - critical for meeting EU traceability requirements and ensuring safe recycling or second-life deployment.

Counterarguments & Rebuttals

Counterargument: Lifecycle data availability will improve, reducing the need for one-shot methods.

Rebuttal: Even with improving standards, real-world fleets will continue to contain legacy batteries, cross-border transfers, fragmented records, and varied data formats. One-shot methods remain indispensable.

Counterargument: One-shot diagnostics cannot reach the accuracy of full-history models.

Rebuttal: Hybrid approaches increasingly close this gap by embedding electrochemical constraints, as evidenced in recent AABC and JSAE research, enabling high accuracy even under minimal data conditions.

Conclusion

Given the persistent absence of consistent lifecycle battery data, **one-shot, hybrid diagnostic approaches are essential** for reliable SoH assessment, regulatory compliance, and sustainable EoL decision-making. Policymakers, OEM-s, and recyclers should prioritize investments in these methods to ensure safe, transparent, and future-proof EV battery value chains.