Evaluating the Benefits of Battery Management System Integration in Modern Lead-Acid Battery Applications

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MOTIVATION

- From Feb 2027: EU regulation mandates a digital battery passport for all traction, light-mobility and industrial batteries >2 kWh, regardless of chemistry
- Lead-acid batteries (LAB) must provide same traceability & life-cycle data as lithium systems
- LAB are highly cost-optimized with thin margins & efficient production processes
- Even small additions (traceability steps, sensors, IT/data work, conformity checks) can cause disproportionate cost increases compared to higher-value lithium batteries

OPPORTUNITIES

- Supports stable circular flows by enhancing traceability, CO_2 accounting and material recovery in already efficient LAB recycling
- Enables better second-life assessment and more accurate residual-value evaluation
- Improves failure and damage analysis
- Reduces warranty and service costs
- More accurate residual-value evaluation of used systems
- Longer lifetime through targeted equalization charging

➢ Objective: development of a modular and cost-efficient BMS for LAB

IMPLEMENTATION

BMS FEATURES

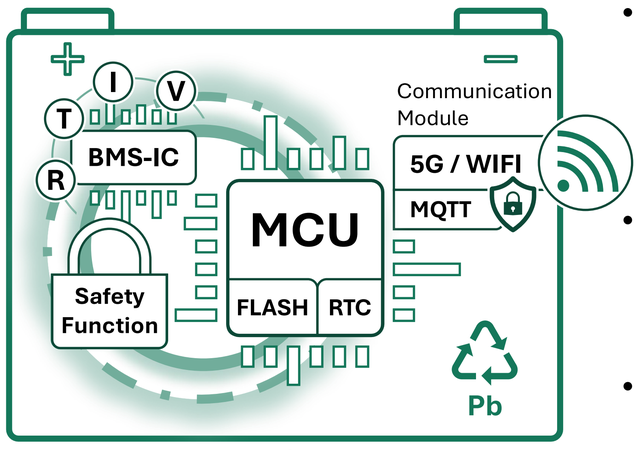

Figure 1: BMS features overview

- Modular and cost-efficient architecture with interchangeable communication modules and application-specific extension boards (e.g., safety, acceleration/position sensing)
- Real-time monitoring of voltage, current, and temperature with automated warnings when operational limits are exceeded
- Preventive diagnostics including on-device estimation of SoC, SoH and SoF
- Automated equalization charging and data-driven optimization of battery operation
- Fully Battery-PASS compliant, providing all required operational and dynamic data

SYSTEM TOPOLOGY

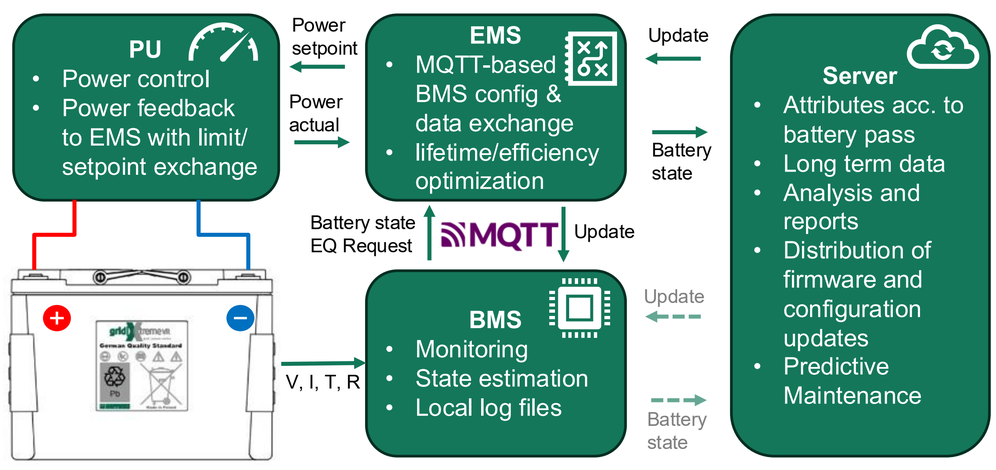

Figure 2: Overview System Topology

- EMS coordinates PU power control and exchanges battery state with the BMS
- Alternatively, the BMS can send measurements and status directly to the server

DATA ECOSYSTEM

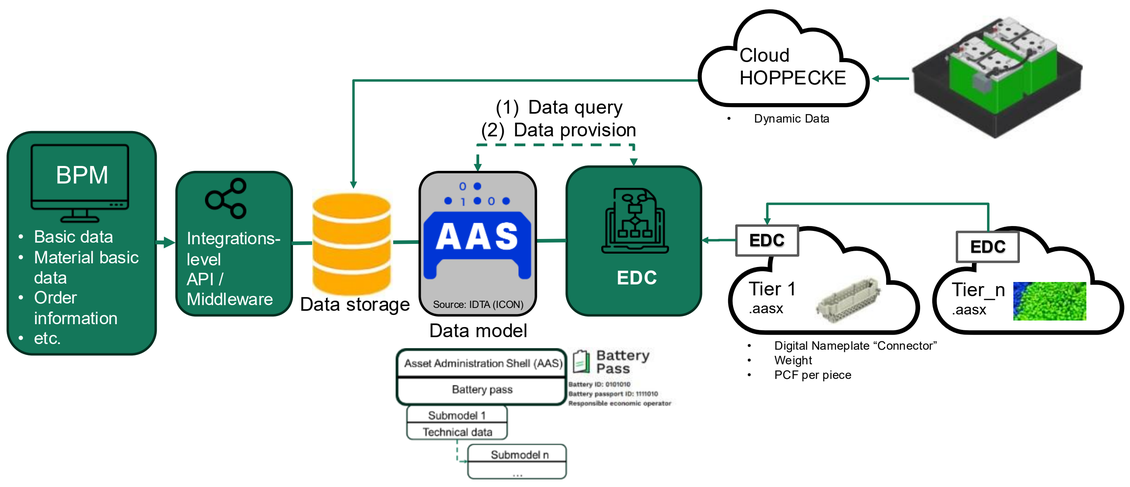

Figure 3: Data Ecosystem

Battery Pass Data Model (AAS-Based Architecture, see fig. 3)

- Standardized digital battery representation via Asset Administration Shell (AAS) organized in submodels
- Unified structure for static, semi-static, and dynamic lifecycle data
- Interoperable across suppliers, OEMs, and cloud systems
- Provides transparency for EU Battery Regulation / Battery Passport Integrated Data Sources
- BPM (Business Processing Management) system: product, materials, order data
- Tier suppliers: Component-level specs (e.g., weights, recycled content)
- OEM cloud platforms: Operational and monitoring data (e.g., HOPPECKE) API / Middleware Layer
- Harmonizes heterogeneous data providers into the AAS
- Provides standardized access and secure, auditable data exchange Lifecycle Data Integration
- Merges production, logistics, operation, and end-of-life data
- Enables full traceability and automated compliance reporting

ALGORITHM

- Reduce sulfation on negative plates while balancing cell voltages

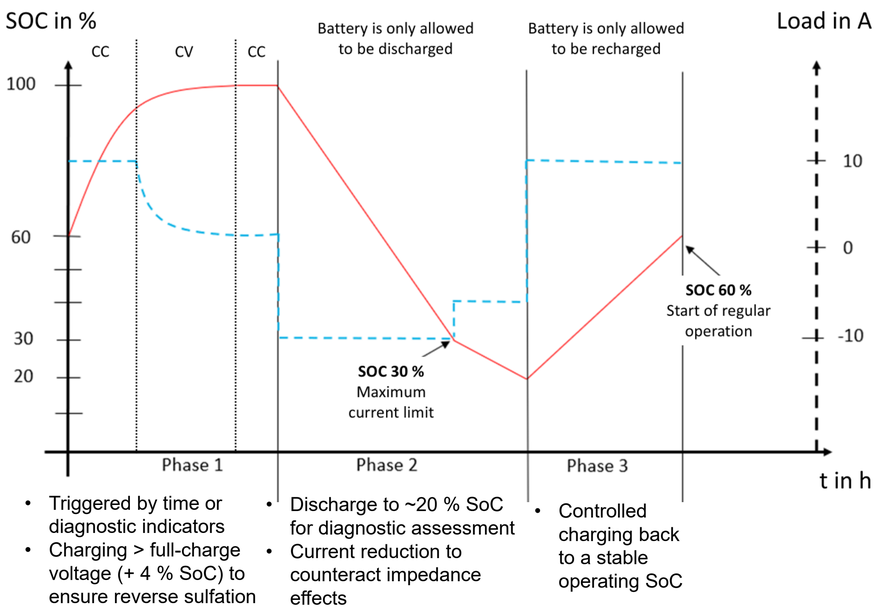

Figure 4: Equalization Charge

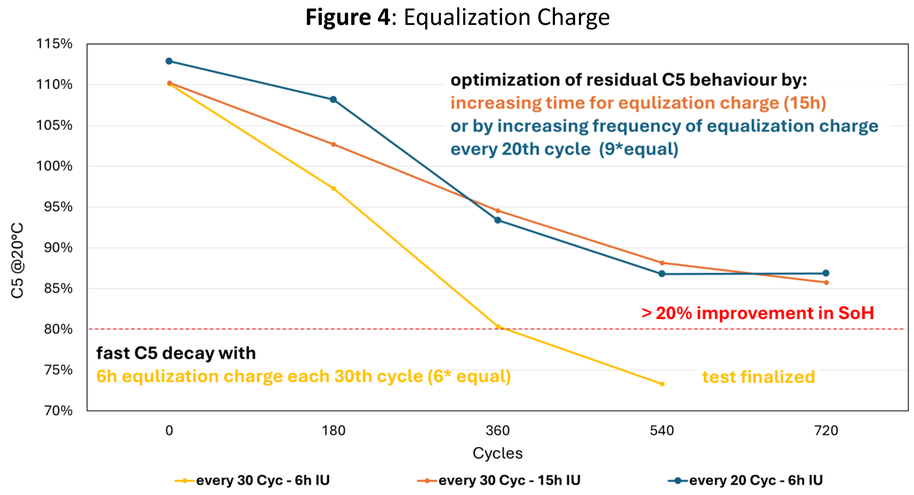

Figure 5: Comparing of Aging test with different equalization charge setup

ECONOMICAL EFFICIENCY

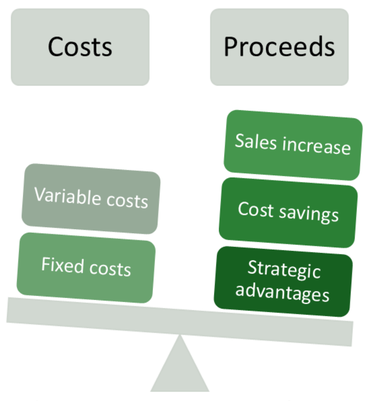

Figure 6: Cost vs. Proceeds

- Analysis of cost-effectiveness of implementing a BMS for LAB
- Implementing costs consist of one-off development, testing & tooling costs, as well as ongoing costs per unit
- Monetized benefits consist of increased sales, cost savings & strategic advantages
- Break-even analysis (see fig. 7) indicates that profitability is achieved within just a few units, especially when accounting for cost savings from reduced warranty claims and more precise failure analyses

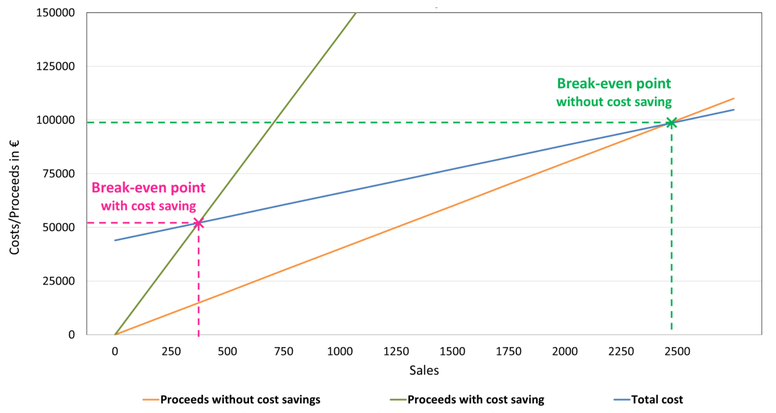

Figure 7: Break-even analysis

SUMMARY AND OUTLOOK

- A modular and cost-efficient BMS for LAB has been developed, providing adaptable interfaces and comprehensive state monitoring
- Real-time diagnostics and an advanced equalization-charge algorithm enhance reliability, reduce degradation, and extend service life (> 20 %)
- The AAS-based Battery-PASS data model enables complete lifecycle transparency and regulatory compliance
- Future work includes extended sensor capabilities, improved degradation modeling, optimized equalization strategies, and enhanced sustainability metrics

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