Abstract

The transition to sustainable transportation depends on the safe, reliable, and economically viable operation of lithium-ion batteries (LIBs). However, their nonlinear electrochemical behaviour, susceptibility to degradation, and uncertainties in lifecycle cost recovery challenge the large-scale adoption of electric vehicles (EVs) and the Battery-as-a-Service (BaaS) model. This thesis develops an integrated framework that links hazard analysis, state estimation, degradation modelling, and lifecycle cost evaluation to address these challenges in a structured and interdependent manner. The work begins with a comprehensive hazard assessment of EV batteries across home charging, public fast charging, and swapping, identifying critical risks such as thermal runaway, degradation, and part failures. Building on this foundation, state of charge (SOC) estimation is developed using nonlinear autoregressive neural networks, benchmarked under real-world drive cycles. Accurate SOC estimation is shown to be vital for range prediction, fair billing, and inventory management in battery swapping stations. Recognizing that SOC accuracy is strongly influenced by battery aging, the study advances to state of health (SOH) estimation and knee point prediction using a hybrid XGBoost–random forest framework combined with slope-change analysis. This enables early detection of accelerated degradation, guiding proactive replacement strategies and ensuring safe deployment of swappable batteries. Finally, a dynamic lifecycle cost recovery model is proposed, integrating SOC, SOH, demand elasticity, monitoring costs, and resale value under ISO 15663 and ISO 55000 standards. Case studies for various fleet segments demonstrate that the model ensures operator profitability while maintaining affordability for users. The interdependency of these objectives defines the novelty of this thesis: hazard analysis ensures operational feasibility, SOC estimation provides real-time reliability, SOH and knee-point prediction secure long-term performance, and the dynamic cost model translates technical findings into actionable economic strategies. Together, these contributions deliver a reliability- and safety-aware framework for LIBs in EV battery swapping, bridging electrochemical performance, operational risks, and financial sustainability.

Keywords: Electric Vehicles. Lithium-ion batteries, State of Charge (SOC), State of Health (SOH), Risk and safety analysis, Battery-as-a-Service (BaaS), lifecycle cost modelling (LCC), Machine learning.