



Building the
Web3 Economy



ELECTRIC VEHICLE BATTERY STATE OF HEALTH BUSINESS WHITE PAPER

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DRIVES PROGRAM

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CONTACT

connect@dlt.mobi
www.dlt.mobi



AUTHORS

Rajat Rajbhandari, MOBI

REVIEWERS

Roger Berg, DENSO
Garrett Graham, Accenture
Toru Kimura, Honda

Christian Köbel, Honda
Pramita Mitra, Ford
Xiaoliang Zhu, Hitachi

CONTRIBUTORS

Praveen Abbaraju, Hitachi
Loren Adams, Accenture
Steve Amancha, State Farm
Jun Amano, Aucnet
Alessandro Arciero, Henshin Group
Daniel Bachenheimer, Accenture
Patrick Bartsch, AWS
Massimo Belluz, Henshin Group
Roger Berg, DENSO
Majiri Birajdar, Arxum
Manuel Bolsinger, BMW
Emmanuel Bulti, Accenture
Elena Carrasco, USAA
Joshua Cartellone, Accenture
Mike Casey, GM
Lucie Chabert, Stellantis
Raullen Chai, IoTEx
Alex Choo, ASJade
Nicola Cianci, Stellantis
Etienne Costet, Stellantis
Kerry Cote, State Farm
Claudia Damari, Henshin Group
Pierre Delunay, Stellantis
Kim Doak-Wiggington, State Farm
Leonard Dorlochter, peaq
Steven Douglas, DENSO
Olivier Emsalem, Stellantis
Xinxin Fan, IoTEx
Aaron Fong, Honda
Sanshiro Fukao, ITOCHU
Mettao Gandolfi, Henshin Group
Fabrizio Garetto, Stellantis
Kamil Gaweda, Arxum
Alan Gordon, Ford
Garret Graham, Accenture
Ivan Guiterrez, State Farm
Kumara Guru, Blockedge
Kawanishi Hiromi, Mazda
Jan ten Hove, TICO
Felix Huang, DENSO
Mikael Johansson, TICO

Yoji Kawanishi, ITOCHU
Toru Kimura, Honda
Yusuke Kitaoka, TICO
Kim Kloeppe, State Farm
Christian Koebel, Honda
Jonathan Koester, peaq
Karthik Krishnamurthy, AWS
Subrata Kundu, Hitachi
Frederic Legrand, Stellantis
Phebe Lu, ASJade
Ishii Makoto, Mazda
Will Maney, USAA
Domenico Mangiacapra, Henshin Group
Piyush Manocha, Accenture
Hisahi Matsumoto, Anritsu
Eiji Matsumura, Anritsu
Hiroaki Murase, ITOCHU
Hideki matsuo, TICO
Lauren Mitchell, State Farm
Emmanuel Monzies, Stellantis
Hiroaki Murase, ITOCHU
Yasuhiro Nakamaya, Aucnet
Taro Nakata, Kaula Lab
Alberto Nasi, Stellantis
Andrea Neri, Stellantis
Keisuke Nisugi, TICO
Rodolfo Occari, TICO
Yasuhiko Ogushi, Kaula Lab
Kenji Ohashi, TICO
Huischi Ohki, Kaula Lab
Haruobu Ohmae, ITOCHU
Katusji Okamoto, Kaula Lab
Shinji Omuro, TICO
Tatsuro Otsu, TICO
Larry Pang, IoTEx
Chrisitan Poullain, Stellantis
Jonas Rahm, TICO
Mathias Renihartz, Stellantis
Futoki Saito, ITOCHU
Yoshihide Sakai, ITOCHU
Davide Salerno, Henshin Group

Shoki Sato, Orico
Otto Schell, Stellantis
Paras Sethi, ParkMyFleet
Kenji Shibata, TICO
Mark Shih, ASJade
Kikuchi Shinchi, Mazda
Erik Skyten, State Farm
Raj Srinivas, Blockedge
Sudha Sriram, Ford
Suresh Sundararaj, Ford
Yuhei Takai, ITOCHU
Kimihiro Tanaka, TICO

Leonardo Tapanelli, Stellantis
Sam Teng, ASJade
Long Tran, AWS
Nanoyama Tsuyoshi, TICO
Takashi Watanabe, Anritsu
Tony Welcome, State Farm
Ross Wheeler, State Farm
Huub van der Wouden, TICO
Hu Xu, TICO
Kubota Yasuyuki, Mazda
Xiaoliang Zhu, Hitachi
Tom Zeibro, Vitesco

MOBI TEAM

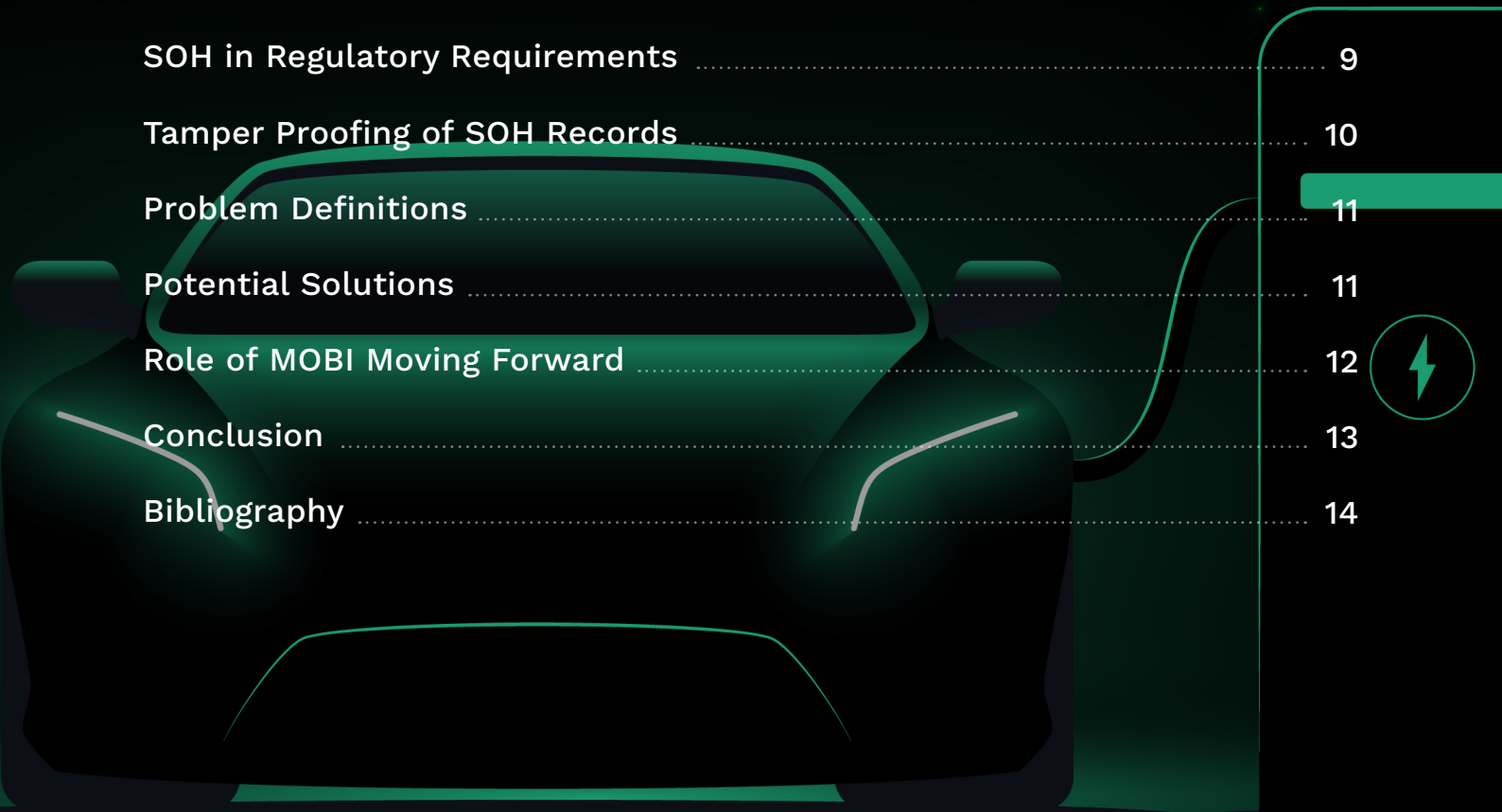
Tram Vo, CEO + Founder
Grace Pulliam, Communications Manager
Chris Ballinger, Advisor + Founder
Andreas Freund, CTO
Parth Bhatt, Technical Product Manager

Rajat Rajbhandari, Head of Standards & Certification
Betul Kahya, Mobility Lead
Matt Shi, Supply Chain Lead
Griffin Haskins, Finance Lead



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EXECUTIVE SUMMARY

Tracking battery performance, or SOH, will be key to unlocking circular business models in the rapidly expanding global EV market.

There is little doubt about the growth of the Electric Vehicle (EV) market globally. One estimate puts it to reach USD 175.11 billion by 2028, at a CAGR of 26.0% during the forecast period of 2021-2028. At the same time, the global EV battery market is projected to grow at a CAGR of 25.3% from USD 27.3 billion in 2021 to USD 67.2 billion by 2025. The market growth of EVs and batteries have created a new set of challenges to the industry.

Although the cost of production is decreasing on a USD/kWh basis, batteries in EVs are one of the most expensive components. Because of the growing EV market, there is an increasing interest in understanding the performance (and degradation) of EV batteries, which is tied to the overall performance of a vehicle and hence its market value. The performance of an EV battery is represented by its State of Health (SOH), more specifically how it changes over time after a vehicle has been in use. There are business models emerging in which EV batteries are repurposed for “second life” after the batteries are deemed unsuitable for EV use because of SOH degradation over time. EV batteries also pose a serious environmental and social challenge if their chemical components are not reused and recycled, which rides upon accurate estimation and tracking of the SOH.

MOBI's Battery SOH Standard investigates current methods for SOH tracking, regulatory compliance requirements, and the emerging need for an industry-wide framework for tracking and sharing SOH data.

MOBI's goal through this document is to provide its stakeholders the state of the art about the battery SOH. It is important for the members to know how the battery SOH is defined, measured, and estimated, and also how the SOH is being used as a key parameter in various business applications and regulatory compliance. With a lot riding on the battery SOH, secure provenance, tamper-evident storage, and reporting of this data between the battery value chain stakeholders will become paramount. There may be a need to create a standardized framework for how the SOH is measured, stored, reported, and provided to stakeholders in the entire battery value chain.

LIST OF ACRONYMS

BMS	:	Battery Management System
BoL	:	Beginning of Life
CARB	:	California Air Resources Board
CBM	:	Circular Business Model
EoL	:	End-of-Life
EU	:	European Union
FCC/DC	:	Full Charge Capacity / Design Capacity
ITN	:	Integrated Trust Network
OEM	:	Original Equipment Manufacturer

RUL	:	Remaining Useful Life
SOH	:	State of Health
SOC	:	State of Charge
ZK	:	Zero-Knowledge

GLOSSARY OF TERMS

This section contains the definitions of all technical and specific terms used throughout this document.

Battery State of Health (SOH): Battery State of Health is the ratio of total maximum capacity (in kWh) at any given time over beginning of life capacity (or rated capacity). The SOH deteriorates over long periods of usage impacting the battery's overall performance.

Battery State of Charge (SOC): Battery State of Charge is the remaining capacity/ total capacity or rated capacity. As the battery ages, remaining capacity decreases.

Battery Management System (BMS): A Battery Management System manages a battery pack and monitors the operating state of modules and cells, calculates and reports various performance data, and balances the performance of individual cells and modules.

Circular Business Model (CBM): It pertains to extending the second life of batteries and extracting as much monetary and environmental benefits as possible until the batteries reach the end of life. At that point, batteries are recycled or completely disposed of.

Second Life of Batteries: Rechargeable batteries after their SOH has reduced and reached a certain level that makes it inefficient for its first intended use, can then be used for other purposes (or second life). For example, EV batteries can be reused for home storage after it has been declared unsuitable for EV use.



OBJECTIVE OF THIS DOCUMENT

This white paper aims to clarify common definitions of battery state of health (SOH), explore business and regulatory implications for EV battery performance, and address potential challenges with proposed solutions for stakeholders.

The objectives of this white paper are fourfold:

- » Identify commonly used definitions of battery state of health (SOH). Determine if there are any conflicts and deviations in the definitions.
- » Gather the state of the art in estimating battery state of health.
- » Outline existing and potential business applications as well as regulatory compliance involving EV battery performance.
- » Identify problems that the stakeholders could face in the foreseeable future and present potential solutions.

DEFINITION OF BATTERY STATE OF HEALTH

Once battery SOH reaches a ratio of 80%, the battery needs to be replaced and the pack repurposed for its second life.

Across academia and industry, the definition of battery SOH was found to be consistent and is calculated by a ratio of total maximum capacity (in kWh) at any given time over beginning of life capacity (or rated capacity). Both sectors agree that when the ratio reaches 80% then the battery has reached its end of life, which means the battery needs to be replaced and the original pack repurposed for its “second life.” Because batteries include cells, modules, and a pack, the definition of SOH carries for individual components in the pack.

As shown in Figure 1, the battery SOH can be also calculated using impedance (or resistance) and represents the thermal limit of the battery. When the SOH is measured using capacity, it is also referred to as “Capacity Fade” as maximum capacity decreases over time.

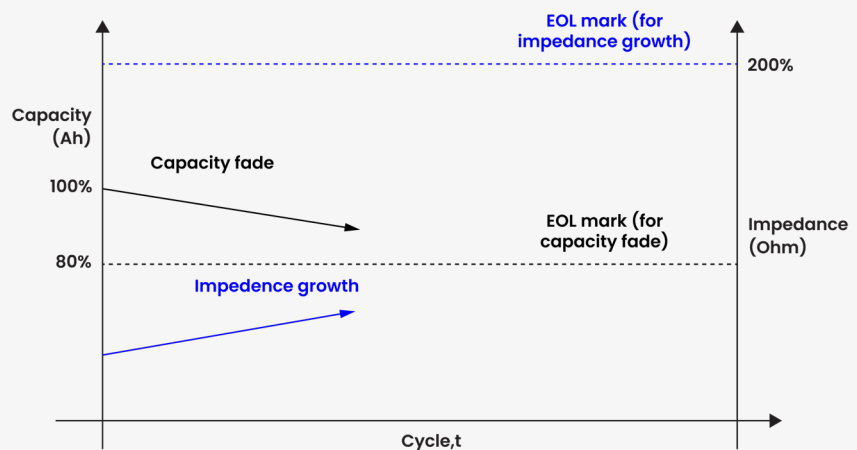


Figure 1. Battery state of health represented by capacity fade and impedance growth

SOH is not the only parameter that defines battery performance and life. State of Charge (SOC) is another key metric for tracking a battery's overall health

There are some disagreements as to whether the SOH should include both capacity fade and impedance growth or just capacity fade. There are arguments about where SOH is adequate to define a battery's overall health. In that case, SOH is not the only parameter that defines battery performance and life. State of Charge (SOC) is also important. SOC is the remaining capacity/total capacity or rated capacity. As the battery ages, remaining capacity decreases.

Nuanced SOH Definitions

In this chapter, we present definitions of SOH in various sources. It shows that the definition of SOH can be quite nuanced.

Panasonic (2019)

“SOH is the ratio between the initial charge and the amount of charge that has deteriorated over time. The amount of charge is measured by the current integration method (Coulomb counting), etc. by a Battery Management System (BMS.) The current SOH can be calculated by storing the charge amount at the start of use and comparing it with the current charge amount. However, SOH has no direct correlation with various lithium-ion battery deterioration phenomena such as electrode deterioration due to metal lithium deposition (dendrites) and electrolyte deterioration. Therefore, the SOH measurement is for obtaining the current charge amount, it cannot estimate the future SOH, and is different from the deterioration diagnosis.”

Texas Instruments (2019)

“Previously, the SOH of a battery was typically represented by the actual runtime FullChargeCapacity/Design Capacity (or FCC/DC). Using the runtime FCC, however, was not a very good representation for the state-of-health because the runtime FCC reflects the usable capacity under load. A high current load reduces the runtime FCC. If using just the FCC/DC calculation for SOH, the SOH under high load will be worse than the SOH under typical load. However, a smaller usable capacity at high load does not mean the SOH of a battery is degraded. This is the same when FCC is reduced at a lower temperature. The SOH is calculated using the FCC simulated at 25C with current specified by SOH Load Rate. The SOH Load Rate can be set to the typical current of the application, and it is specified in hour-rate (that is, **Design Capacity/SOH Load Rate will be the current used for the SOH simulation**).”

Li et al (2020)

“The SOH of the battery is a metric to indicate the battery’s aging level. The commonly used SOH indices can be divided into two groups: capacity fade indices and power fade indices. With battery aging, the value of the remaining capacity of the battery will decrease because of the capacity loss mechanisms, resulting in the capacity fade of the Battery. In this work, the SOH indicating the battery’s capacity fade, SOHC, and the SOH indicating the battery’s power fade, SOHR, are determined synchronously.

The SOHC of the battery is usually defined as follows = $C_{N,t} / C_{N,0}$

where $C_{N,0}$ and $C_{N,t}$ are the nominal capacity and the remaining capacity at current time t .

*The SOHR of the battery is determined = $R_{0,t} / R_{0,0}$ *

where $R_{0,0}$ and $R_{0,t}$ are the ohmic resistance at battery's begin of life (BoL) and current time t .

The End of Life (EOL) of the battery regarding the capacity fade is reached when the value of SOHC, t as shown in (29), equals 80%. However, the EOL can also be defined as the time that the value of the ohmic resistance increases 30%, i.e. the value of SOHR, t reaches 130%, considering the battery's power fade, as shown in (30). Therefore, it is essential to estimate both SOHC, t and SOHR, t at the same time.”

Lina et al (2015)

“In order to evaluate the aging level of lithium-ion batteries, several indicators or notions are created. The state of health is the most-used indicator in the literature. Meanwhile, the relative capacity which interprets SOH and capacity loss of batteries. The cell relative capacity could be calculated by the following equation.

$$C_{relative} = C_{np}/C_{n0}$$

where C_{np} represents the capacity of current cells, C_{n0} represents the initial capacity of a cell before the cycle test, and $C_{relative}$ represents the relative capacity of current cells. Generally, the battery is considered to reach its end of life when the battery capacity fades to 80% of its initial value. This indicator represents the battery fades.”

Li et al (2020)

“SOH is calculated by the common judgment method of current research capacity, that is, the ratio of the maximum amount of electricity released by the battery in the use of the vehicle to the factory capacity marked on the nameplate of the vehicle battery, as shown in $SOH = Q_{aged} / Q_{new}$ ”

Bak et al (2019)

“In order to manage the battery efficiently, it is necessary to accurately estimate and manage the battery SOH and Remaining Useful life (RUL). SOH represents the maximum discharge capacity to the rated capacity of batteries. Since the maximum discharge capacity is characteristic of battery aging, SOH is used as an indicator of degree of aging. SOH of the new battery with no degradation is processed in 100%. When SOH value reaches 80%, that is the time for the replacement and can be regarded as reaching an EOL. RUL represents the remaining life until the EOL.”

Murnane and Ghazel

“A fully charged battery has the maximal releasable capacity (C_{max}), which can be different from the rated capacity. In general, C_{max} is to some extent different from C_{rated} for a newly used battery and will decline with the used time. It can be used for evaluating the SOH of a battery.

$$SOH = C_{max}/C_{rated}$$

Singh et al (2019)

“Theoretically, the SoH of a fresh battery is 100% and will decrease over time due to its usage. SOH is an indicator to describe the health status of a battery, and it can reflect the performance and aging of the battery. In terms of electrical quantity, SOH is an indicator of the remaining full battery capacity. SOH is generally defined as the ratio of the maximum releasable capacity of a battery to the rated capacity of the battery when it is fresh.”

SOH ESTIMATION METHODS

Estimating the SOH of Lithium-Ion batteries is challenging due to various aging factors. SOH estimation methods fall into two broad categories: experimental methods and model-based methods.

Estimating SOH is complicated as many factors from the ambient environment or from charge and discharge cycles generate different aging effects. This makes the SOH estimation a difficult task, and throughout the years, many studies have tried to explore the aging mechanisms.

According to Noura et al (2020), there are two broad categories of SOH estimation methods for EV Lithium Ion batteries. Those categories are following:

Experimental methods - direct measurement of impedance, internal resistance, capacity levels using laboratory devices such as spectroscopy.

Model-based methods - based on physical equations and curve fitting, machine learning algorithms.

Experimental methods are typically conducted in laboratories with specific equipment and are often time consuming (several hours). These methods measure battery internal resistance and impedance using techniques such as Electrochemical Impedance Spectroscopy and measure battery internal resistance behavior in different working conditions with a very satisfying accuracy.

Model-based methods are more feasible for realtime deployment but can be rendered useless by unexpected changes in the operating conditions.

Model-based methods use empirical models, curve fitting, statistical linear and non-linear models, differential equations, machine learning, neural networks, etc., to estimate SOH or capacity degradation over time and into the future. Due to their real time feasibility, model-based methods for estimating SOH have gathered significant interest in the industry. Model-based methods can be deployed in the BMS. However, any deviation from the training data because of new operating conditions can render the estimation useless.

A combination of experimental and model-based methods has also been proposed. In this method, data gathered from the experimental methods are used as training data sets and fed into model-based methods. The availability of such data is beneficial to methods that use neural networks that by nature require large data sets.

The key issue is finding the ideal compromise between experimental and modelbased methods to ensure accuracy, cost efficiency, and real-time reporting capabilities.

Obtaining a complete battery SOH diagnosis considering every aging factor and compatibility with an EV application remains a major challenge. Currently, the key issue for aging estimation is finding the ideal compromise between various methods considering their application in EVs.

BUSINESS APPLICATIONS OF SOH

Battery SOH data will be a powerful tool for stakeholders across the value chain to unlock more transparent and sustainable business models.

As rechargeable batteries become more and more ubiquitous, discussions about their performance (as well as methods of estimation) will become more prominent. End consumers will want to know initial SOH and how it will degrade over time for the vehicle of their choice before making purchasing decisions. Insurance companies may want to know the residual value of batteries to correctly underwrite them. Lenders would want to know whether to extend the warranty of the vehicle or not.

The following section outlines use cases/applications of battery SOH from the perspectives of various stakeholders:

End Users (Vehicle and Fleet Owners):

Vehicle owners can use SOH data to determine when to replace a battery and assess their EV's value based on remaining capacity.

The SOH is used in determining the current maximum range of EVs. Current maximum range of an EV = current SOH x rated beginning of life range = 90% x 300 km = 270 km.

Vehicle and fleet owners can use this information to determine time remaining before the battery has to be replaced and compare their EV's value based on remaining capacity.

Insurance Companies:

Insurers will be able to leverage battery SOH data for underwriting purposes.

Insurance companies may require correct assessment of battery performance to estimate the battery replacement costs or underwrite battery warranties. Insurance giant Munich Re recently announced that it will offer a product that covers battery performance (Munich Re, 2019). Their product allows manufacturers in the battery market to offer long-term performance guarantees whose value is backed by the insurance coverage.

According to their website, "The new coverage allows battery manufacturers to insure their customer warranties. For example, if the repair or replacement costs of defective or weak battery modules exceed a predetermined amount, the insurance then covers the rest. Manufacturers can thus unburden their balance sheets."

OEMs and Battery Suppliers:

Battery performance, especially the SOH, will be a key parameter that will influence consumers' vehicle buying choices.

Because batteries are a critical component of EVs, an EV's range — and, by extension, its value — will be tied to the battery's performance. Battery performance, especially the SOH, will be a key parameter that will influence consumers' vehicle buying choices. OEMs are also responsible for battery recalls, maintenance services, and management of battery warranties. Both OEMs and suppliers will have a responsibility to comply with future regulations regarding standardized reporting of SOH as well as battery recycling/repurposing.

SOH in the Battery Passport

Battery SOH is one of the key attributes the battery passport will track and make available to stakeholders in the value chain.

Battery Passport is a tool being developed by the Global Battery Alliance and other vendors such as EverLedger to track the life cycle of batteries, including second life. Battery SOH is one of the key attributes the passport will track and make available to stakeholders in the battery value chain.

SOH in Circular Business Models

Circular business models assume that second life or repurposing will increase business opportunities for stakeholders and reduce the burden on recycling, which can be quite expensive.

Circular Business Models (CBMs) pertain to extending the second life of batteries and extracting as much monetary and environmental benefits as possible until the end of life (Olson et. al., 2018). For example, EV Batteries with < 80% SOH can still be used for other purposes such as home energy storage (Clement et. al., 2020). There is no clear consensus at which point the OEMs send the modules to recyclers and for how long recyclers continue to use the modules for different uses such as home energy.

These models assume that second life or repurposing will increase business opportunities for stakeholders and reduce the burden on recycling, which can be quite expensive. Hence, CBMs extend the value chain of batteries beyond first life.

CBMs will require close collaboration between different stakeholders to build trust and reduce uncertainties regarding the performance of the battery and its individual components. It appears CBMs rely not only on being able to accurately determine the performance of batteries but also on how quickly these measures (e.g., SOH) can be determined (Albertson et. al., 2021).



SOH IN REGULATORY REQUIREMENTS

European Union's Proposed Battery Directive

The proposed Battery Directive builds on commitments and reports adopted by the European Commission, including the strategic action plan on batteries, the new circular economy action plan, the new industrial strategy for Europe, and the sustainable and smart mobility strategy.

In 2020, the European Commission published a proposal for Regulation of the European Parliament and of the Council concerning batteries and waste batteries (EU, 2020). This proposal aims to modernize the EU's legislative framework for batteries. It builds on commitments and reports adopted by the European Commission, including the strategic action plan on batteries, the new circular economy action plan, the new industrial strategy for Europe, and the sustainable and smart mobility strategy, which aims at delivering a 90% reduction in transport-related GHG emissions by 2050.

The proposal's objectives are threefold:

- » Strengthening the functioning of the internal market (including products, processes, waste batteries, and recycles), by ensuring a level playing field through a common set of rules.
- » Promoting a circular economy.
- » Reducing environmental and social impacts throughout all stages of the battery life cycle.

The proposal considers second life of batteries (repurposing), collection targets, recycling and recovery of materials, carbon footprint declarations, and information management of battery performance throughout the lifecycle. The proposal specifies that the end of life criteria of batteries include a state of health check before being sent to repurposing or recycling.

Article 14 specifically requires rechargeable industrial and EV batteries to include a battery management system that tracks state of health and expected lifetime, with data access provided to buyers and third parties to facilitate battery reuse, repurposing, and participation in electricity grids.

Article 14 of the proposal requires that

...rechargeable industrial batteries and electric vehicle batteries shall contain a battery management system that stores the information and data needed to determine the state of health and expected lifetime of batteries in accordance with the parameters laid down in Annex VII. Access to the data on those parameters in the battery management system shall be provided to the legal or natural person who has legally purchased the battery or any third party acting on their behalf at any time for evaluating the residual value of the battery, facilitating the reuse, repurposing or remanufacturing of the battery and for making the battery available to independent aggregators operating virtual power plants in electricity grids.

Article 59 requires operators to provide state of health evaluation evidence to confirm a battery is no longer waste, and this information must be included in the technical documentation for repurposed batteries when marketed or put into service.

Article 59 requires that in order to document that a battery is no longer waste, the operator carrying out the relevant operation shall demonstrate the following upon request by a competent authority amongst other parameters the evidence of state of health evaluation or testing and that this information shall be made available to end users and third parties acting on their behalf, on equal terms and conditions, as part of the technical documentation accompanying the repurposed battery when placed on the market or put into service.

SOH Standardization Proposal by the California Air Resources Board

Draft regulations from the California Air Resources Board (CARB) establish a standardized set of procedures for vehicle manufacturers related to SOH tracking and reporting.

In December of 2021, the California Air Resources Board (CARB) presented draft regulations establishing a zero-emission in-use verification report to be submitted by the vehicle manufacturers to CARB (CARB, 2021). These regulations establish enforcement testing procedures to be used by CARB to periodically evaluate vehicles for compliance in addition to procedures and requirements for remedial actions.

The regulation will require OEMs to calculate battery SOH such that it is:

- » Readable by drivers without a tool.
- » Normalized (100% equals new on all cars).

The regulation will also require OEMs to define and disclose SOH value that qualifies for warranty repair.

TAMPER PROOFING OF SOH RECORDS

For use cases such as Battery Passport and others mentioned in previous sections, it is clear that the industry will require tools by which the battery's SOH values are tamper-proof and tamper-evident.

For use cases such as Battery Passport and others mentioned in previous sections, it is clear that the industry will require tools by which the battery's SOH values are tamper-proof and tamper-evident. Such a requirement will allow the stakeholders to trust the validity of the SOH data with a high confidence. The SOH values measured by the maintenance service providers and by the BMS must be tamper-proof. The need for such a requirement is the same as and even greater than tamper-proofing the odometer reading in vehicles.

Blockchain technology has been proposed by Ding, Gowda et. al., and Florea et. al., to create a framework to secure SOH values of EV batteries.

Ding (2018) proposed creating a hash of battery test reports and storing the transaction in a consortium blockchain. That way other stakeholders in the value chain can share and verify the correctness of the test reports and values with regard to the SOH. Gowda et. al. (2021) proposed a similar concept of storing battery SOH data and the cost of degradation in a consortium blockchain for the electric vehicle grid integration use case. Florea (2020) proposed a blockchain application for the electric vehicle battery charge and swap use case. The battery voltage and state of charge (SOC) is continuously monitored and the data is stored on the blockchain together with the required functionalities such as user and battery information and charge/swap requests.

PROBLEM DEFINITIONS

The identified problems include the absence of industry-wide standards for defining and presenting battery SOH to stakeholders, unclear value chain mapping for those needing SOH information, and a lack of a framework for creating tamper-proof SOH records.

Following is a list of problems identified in the earlier chapters:

- » Lack of industry-wide standards to define and present battery SOH to end users and other value chain stakeholders for various use cases (i.e., recollection, repurposing, and recycling) including comparing performance of new and used batteries.
- » Lack of clarity in value chain mapping of stakeholders that require SOH information.
- » Lack of industry-wide requirements/framework to create tamper-proof/tamper-evident battery SOH records, which covers the following - verification system is needed for trust among vehicle OEMs and battery manufacturers to be incentivized for recycling programs to either share SOH values or the parameters necessary for third parties to calculate and monitor battery performance for the purposes described in the problems above.

POTENTIAL SOLUTIONS

Potential solutions include developing industry standards for SOH, mapping stakeholder value chains, and creating tamper-proof frameworks for SOH data exchange.

- » Solution(s) for Problem 1: Create an industry standard definition of SOH. Develop a guideline for how SOH information should be consumed by the stakeholders for various use cases.
- » Solution(s) for Problem 2: Comprehensive value chain mapping of stakeholders and various business applications that require SOH. The mapping should include provenance of SOH information between stakeholders for the use cases discussed previously. Following the mapping, a detailed analysis of the EV battery value chain will be helpful for the industry to understand the potential bottlenecks, risks, and opportunities for SOH reporting and consumption.
- » Solution(s) for Problem 3: It is imperative from the literature review that the SOH information will be valuable data upon which many business applications will rely. The same way there are many applications and processes in place to ensure tamper proofing of odometer readings, the industry should develop frameworks to ensure the SOH information is tamper-proof and tamper-evident.



ROLE OF MOBI MOVING FORWARD

MOBI VID supports monetization of the massive bi-directional data flows from connected vehicles.

MOBI ecosystem includes a diverse set of battery value chain stakeholders. From the literature view above, it is clear that the ecosystem requires open standards, frameworks, and reference implementations to define, gather, share, and present tamper-evident battery SOH related information and history, especially in second life use cases. MOBI is working on decentralized battery identities based on W3C standards and building the Web3 infrastructure:

- » The Integrated Trust Network (ITN) is a protocol-agnostic digital infrastructure to provide trusted identity services.
- » Citopia is a decentralized marketplace to onboard Self-Sovereign Digital Twins and enable Verifiable Credentials issuance for business automation using Zero-Knowledge (ZK) Proofs. Citopia enables countless track and trace use cases in the supply chain and unlocks marginal cost pricing for numerous mobility-as-a-service transactions.

Stakeholders can use MOBI's Web3 infrastructure to enhance trusted data sharing and interoperability in the battery supply chain.

Battery and EV stakeholders can use MOBI standards and the Web3 infrastructure to create traceable and tamper-evident multi-party applications to share the SOH related information with other stakeholders in the battery value chain. These applications could include:

- » Information about the battery manufacture for purposes of monitoring sourcing, sustainability, carbon footprint, and supply chain efficiency, etc.
- » Information about the battery use and health for purposes of establishing value, battery swapping, suitability for decentralized green energy storage, etc.
- » Information about second and third uses and ultimately disposal.



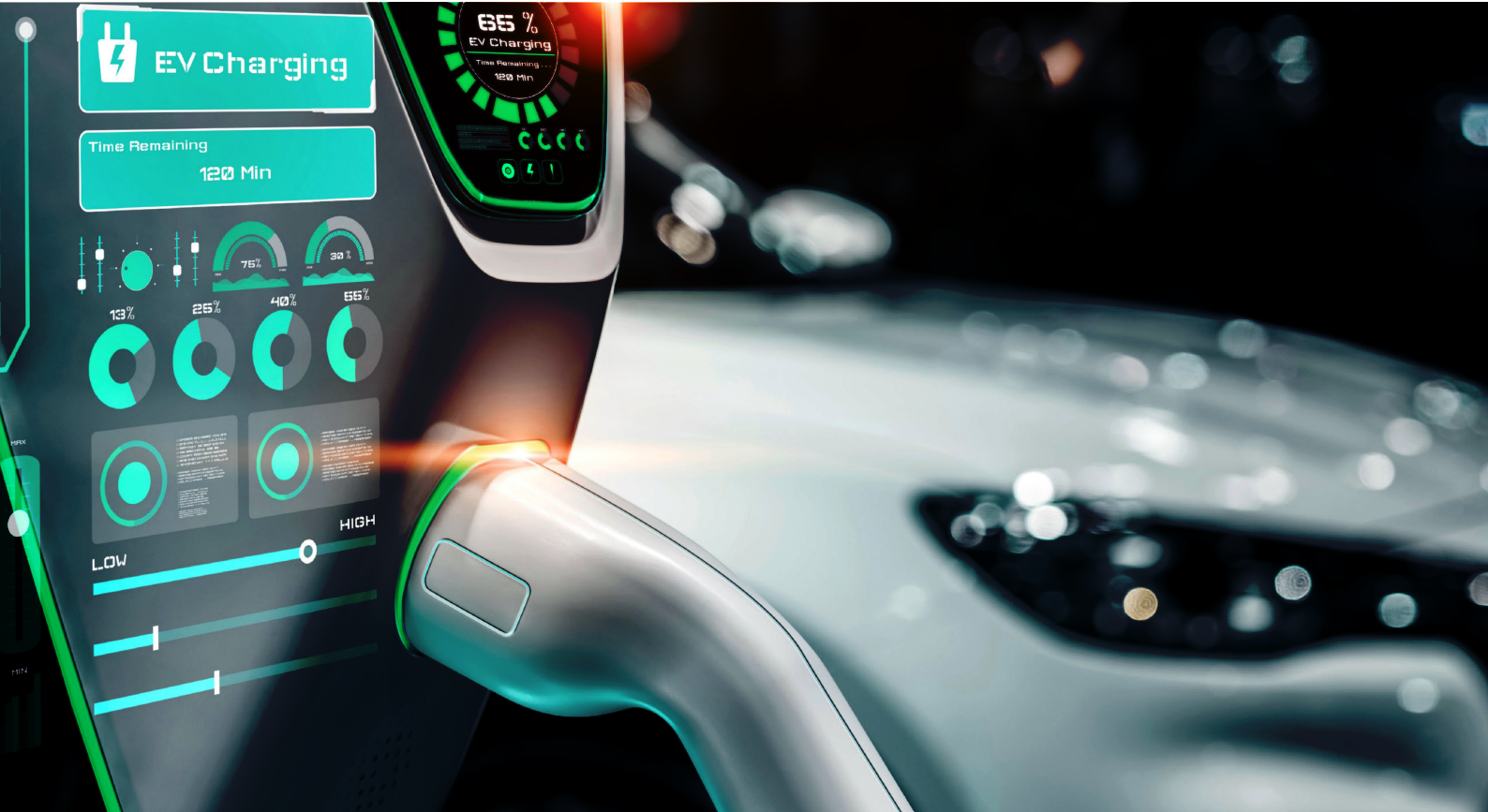
CONCLUSION

This white paper examines battery SOH estimation methods, key use cases, and highlights the need for tamper-proof reporting to meet regulatory standards.

This white paper investigates the state of art/ current landscape in battery SOH in various ways. Firstly, we discuss definitions of battery SOH across different literature and SOH estimation methods used today including model based and experimental methods and combined methods as well as challenges associated with these methods. Obtaining a complete battery SOH diagnosis with a cost and time effective, accurate and scalable method remains a challenge for the industry.

This paper also explores, at a high level, different use cases for battery SOH applications for OEMs, battery suppliers, insurers and end-users. The white paper also discusses regulatory requirements in EU's battery directive and CARB regulations in California. As a result of the requirements of regulations set forth and in development, it seems evident that the industry will need the SOH values reported to be tamper-proof and tamper-evident.

We identified the lack of industry-wide standards battery SOH definition and presentation, lack of clarity in the SOH data flow among the stakeholders in the value chain and the lack of industry-wide requirements/framework to create tamper-proof/tamper-evident battery SOH records as the main challenges in this landscape. We propose the following solutions to these challenges respectively, by creating an industry standard definition of SOH, conducting a comprehensive value chain mapping of stakeholders and various business applications that require SOH and creating frameworks tamper-proof and tamper-evident SOH records.



BIBLIOGRAPHY

- “Advanced Clean Cars (ACC) II Workshop.” CARB, May 6, 2021.
https://ww2.arb.ca.gov/sites/default/files/2021-05/acc2_workshop_slides_may062021_ac.pdf.
- Albertsen, Levke, Jessika Luth Richter, Philip Peck, Carl Dalhammar, and Andrius Plepys. “Circular Business Models for Electric Vehicle Lithium-Ion Batteries: An Analysis of Current Practices of Vehicle Manufacturers and Policies in the EU.” *Resources, Conservation and Recycling* 172 (September 2021): 105658. <https://doi.org/10.1016/j.resconrec.2021.105658>.
- Bak, Taejun, and Sukhan Lee. “Accurate Estimation of Battery SoH and RUL Based on a Progressive LSTM with a Time Compensated Entropy Index.” *Annual Conference of the PHM Society* 11, no. 1 (2019). <https://doi.org/10.36001/phmconf.2019.v11i1.833>.
- “Battery Performance Now Insurable – Innovative Munich Re Coverage Paves the Way for Renewable Energy.” Munichre.com. March 7, 2019. <https://www.munichre.com/en/company/media-relations/media-information-and-corporate-news/media-information/2019/2019-03-07-battery-performance-now-insurable-innovative-munich-re-coverage-paves-the-way-for-renewable-energy.html>.
- Clement, Sarah, and Lisa Ruf. “UK Energy Storage Lab Project - Public Report.” Element Energy Ltd, January 2020.
- Ding, Peng. “A Battery Health Data Sharing Model via Blockchain.” *OALib* 05, no. 11 (2018): 1–12. <https://doi.org/10.4236/oalib.1105016>.
- European Commission. “Proposal for a Regulation of the European Parliament and of the Council Concerning Batteries and Waste Batteries, Repealing Directive 2006/66/EC and Amending Regulation (EU) No 2019/1020.” 2020. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0798>.
- Florea, Bogdan Cristian, and Dragos Daniel Taralunga. “Blockchain IOT for Smart Electric Vehicles Battery Management.” *Sustainability* 12, no. 10 (2020): 3984. <https://doi.org/10.3390/su12103984>.
- “Global Electric Vehicle Battery Market Research Report 2021: Patent Analysis, Raw Materials, Market Dynamics, Competitive Landscape, Forecasts.” Yahoo.com, December 14, 2021. ResearchAndMarkets. <https://www.yahoo.com/now/global-electric-vehicle-battery-market-200000634.html>.
- Gowda, Shashank Narayana, Basem A. Eraqi, Hamidreza Nazaripouya, and Rajit Gadh. “Assessment and Tracking Electric Vehicle Battery Degradation Cost Using Blockchain.” 2021 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2021. <https://doi.org/10.1109/isgt49243.2021.9372218>.
- Li, Peiqing, Huile Wang, Zixiao Xing, Kanglong Ye, and Qipeng Li. “Joint Estimation of SOC and SoH for Lithium-Ion Batteries Based on EKF Multiple Time Scales.” *Journal of Intelligent Manufacturing and Special Equipment* 1, no. 1 (2020): 107–20. <https://doi.org/10.1108/jimse-09-2020-0008>.
- Li, Weihang, Monika Rentemeister, Julia Badeda, Dominik Jöst, Dominik Schulte, and Dirk Uwe Sauer. “Digital Twin for Battery Systems: Cloud Battery Management System with Online State-of-Charge and State-of-Health Estimation.” *Journal of Energy Storage* 30 (2020): 101557. <https://doi.org/10.1016/j.est.2020.101557>.

Lin, Cheng, Aihua Tang, and Wenwei Wang. "A Review of SOH Estimation Methods in Lithium-Ion Batteries for Electric Vehicle Applications." *Energy Procedia* 75 (2015): 1920–25. <https://doi.org/10.1016/j.egypro.2015.07.199>.

Markets and Markets. "EV Battery Market by Battery Capacity (<50, 50-110, 111-200, 201-300 and >300), Battery Form (Wire, Laser), Propulsion (BEV, PHEV, FCEV), Battery Type, Material Type, Li-ion Battery Component, Method, Vehicle Type & Region - Global Forecast to 2025." March 2021. <https://www.marketsandmarkets.com/Market-Reports/electric-vehicle-battery-market-100188347.html>.

Murnane, Martin and Ghazel Adel, 2017. "A Closer Look at State of Charge (SOC) and State of Health (SOH) Estimation Techniques for Batteries." *Analog Devices*, pp.1-8. <https://www.analog.com/media/en/technical-documentation/technical-articles/a-closer-look-at-state-of-charge-and-state-health-estimation-techniques.pdf>.

Noura, Nassim, Loïc Boulon, and Samir Jemeï. "A Review of Battery State of Health Estimation Methods: Hybrid Electric Vehicle Challenges." *World Electric Vehicle Journal* 11, no. 4 (2020): 66. <https://doi.org/10.3390/wevj11040066>.

Olsson, Linda, Sara Fallahi, Maria Schnurr, Derek Diener, and Patricia van Loon. "Circular Business Models for Extended EV Battery Life." *Batteries* 4, no. 4 (2018): 57. <https://doi.org/10.3390/batteries4040057>.

"Panasonic Develops Battery Management Technology to Measure Electrochemical Impedance of Multi-Cell Stacked Lithium-Ion Batteries." *News.panasonic.com*, November 14, 2019. Panasonic. <https://news.panasonic.com/global/press/data/2019/11/en191114-2/en191114-2.html>.

Singh, Preetpal, Che Chen, Cher Ming Tan, and Shyh-Chin Huang. "Semi-Empirical Capacity Fading Model for SOH Estimation of Li-Ion Batteries." *Applied Sciences* 9, no. 15 (2019): 3012. <https://doi.org/10.3390/app9153012>.

Texas Instruments. "Technical Reference." SLUUBU5A. January 2019–Revised February 2019.

