BATTERY2LIFE

D1.2 Open-source and interoperable BMS principles

Co-funded by the European Union

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor CINEA can be held responsible for them.

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

DOCUMENT CONTROL TABLE

Work Package	WP1
Task	T1.2 Challenges to open-source and interoperable BMS design
Author(s)	E. Karfopoulos (ICCS), I. Aizpurua (CID), M. Koller (AIT), Y. Stauffer (CSEM), D. Spanoudaki (SLG), L. Thumfart (MIBA)
Dissemination Level	Public
Status	Final_Draft
Due Date of submission	30/06/2024
Actual Date of submission	
Document Date	30/05/2024
Version	0.3
Project Name	BATTERY Management system and System design for stationary energy storage with 2nd LIFE batteries
Project Acronym & Number	Battery2Life 101137615
Project Website	www.battery2life-project.eu
Project Social Media	@battery2life_eu & BATTERY2LIFE Project

QUALITY CONTROL

	Name	Organisation	Date
Editor	E. Karfopoulos	ICCS	14/06/2024
Reviewer 1	J.A. Jiménez Caballero	UNE	17/06/2024
Reviewer 2	Rigas Frangoudis	SLG	17/06/2024
Authorised by Quality Manager	E. Karfopoulos	ICCS	26/06/2024
Authorised by Project Coordinator	Angelos Amditis	ICCS	27/06/2024

DOCUMENT HISTORY

Version	Date	Modification	Partner
v0.1	01/03/2024	Draft ToC / Template for challenges towards open BMS	E. Karfopoulos (ICCS)
v0.2	30/05/2024	1st draft version – state machine diagrams	Izaskun Aizpurua (CID), Koller Markus (AIT) E. Karfopoulos (ICCS), Y. Stauffer (CSEM), L. Thumfart (MIBA)
v0.3	14/06/2024	Revisions from partners	Izaskun Aizpurua (CID), Rigas Frangoudis (SLG)
v0.4	18/06/2024	Revisions based on peer-reviewing	J.A. Jiménez Caballero (UNE), Rigas Frangoudis (SLG)
V1.0	27/06/2024	Final Ready for submission	E. Karfopoulos (ICCS)

LEGAL DISCLAIMER

CONTENTS

TABLE OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation	Meaning
API	Application Programming Interface
BESS	Battery Energy Storage System
BMS	Battery Management System
B2L	Battery2Life
CAN	Controller Area Network
DB	Database
DPP	Digital Product Passport
DRT	Distribution of Relaxation Time
ECM	Equivalent Circuit Model
EIS	Electrochemical Impedance Spectroscopy
EKM	Extended Kalman Filter
EMC	Electromagnetic Compatibility
EMS	Energy Management System
EoL	End of Life
ESS	Energy Storage Solution
EV	Electric Vehicle
FL-EOL	First-Life End-Of-Life
GBA	Global Battery Alliance
HTTP	Hypertext Transfer Protocol
IP	Intellectual Property
I2C	Inter-Integrated Circuit
MCU	Master Control Unit
MMS	Module Management System
MQTT	Message Queuing Telemetry Transport
OEM	Original Equipment Manufacturer
OTA	Over The Air
PCB	Printed Circuit Board
PV	Photo Voltaic
P2P	Provider To Provider

Co-funded by the European Union

RES	Renewable Energy Systems
RH	Remaining Health
RUW	Remaining Useful Warranty
RW	Remaining Warranty
SOA	Safe Operation Area
SoC	State of Charge
SoF	State of Functions
SoH	State of Health
SoS	State of Safety
SoT	State of Temperature
SoW	State of Warranty
SoX	State of Battery (ex. SoH, SoS, SoT, etc)
SPI	Serial Peripheral Interface
TRA	Thermal Runaway
USB	Universal Serial Bus

EXECUTIVE SUMMARY

This deliverable provides a high-level description of the hybrid BMS approach adopted in the Battery2Life project, presenting key deployment challenges for an open and interoperable BMS. Additionally, it includes state machine diagrams of the BMS estimators and outlines the information flows between the cloud and edge BMS.

This document acts as an introduction to the project deliverable D1.3 “*BMS specifications and advanced algorithms for 2nd life*” where the detailed BMS hardware and software specifications are detailed.

Co-funded by the European Union

1 INTRODUCTION

1.1 Project Introduction

BATTERY2LIFE is a project, funded by Horizon Europe programme (co-funded by Swiss Federation) that will facilitate the smooth transition of batteries to 2^{nd} life use and will boost the innovation of the European Battery Industry by providing enablers to implement open adaptable smart Battery Management Systems (BMS), improved system designs and proposing methods for the efficient and reliable reconfiguration of used batteries.

Battery2Life introduces two new battery system design frameworks serving the upcoming market needs: the first supports the business transition for the initial market by restructuring existing battery design patterns while the second one introduces completely new design principles for 1st and 2nd life of future batteries. Furthermore, Battery2Life introduces innovative embedded sensing and more accurate SoX (State of Battery) estimation algorithms, which are also required for 2nd life use (i.e. SoS (State of Safety) and SOW (State of Warranty)). A new Electrochemical Impedance Spectroscopy (EIS) implementation approach is integrated into the BMS, that will enable the detailed safety and reliability monitoring at both cell and module level during 1^{st} and 2^{nd} life stage usage. The project specifies an open BMS concept, data formats, considerations, extends the battery passport concept, and implements interoperable communication via the cloud platform to third parties including the future passport exchange system, to facilitate monitoring and assessment.

Two demonstrations that represent two promising and sustainable business cases, serving the two most common stationary applications have been carefully selected: i) the domestic and ii) industrial (grid-scale) storage, with respect to their operational specificities and requirements.

1.2 Purpose of the deliverable

This deliverable aims to analyse the project approach towards open and interoperable BMS by introducing a hybrid cloud/edge BMS architecture serving two different business use cases for the exploitation of 2^{nd} life batteries: a) industrial load levelling application and b) domestic storage application. Furthermore, the state machine diagrams of the different BMS processes for both business use cases are explained.

1.3 Intended audience

Deliverable D1.2 is a public document aiming to analyse the project approach towards open and interoperable BMS.

The document aims to inform academic institutions and technical experts interested in the latest advancements in open-source and interoperable BMS technology. Overall, it seeks to engage a broad audience committed to the development and implementation of second-life battery applications.

1.4 Structure of the deliverable/correlation with other WPs

The deliverable comprises two sections:

- **Open and interoperable BMS:** it provides an overview of the key challenges towards open and interoperable BMS for 2nd life battery applications.
- **B2L BMS approach:** it analyses the project BMS architecture as well as the state machine diagrams for the BMS processes to be implemented in the project 2nd life battery storage applications.

2 OPEN AND INTEROPERABLE BMS

2.1 Paving the way from 1st life to 2nd life batteries from EVs

The transition to a carbon neutral transportation sector, particularly in road transport, which is a major pollutant sub-sector[1], has been underway for over a decade. During this period, the market share of Electric Vehicles (EVs) has significantly increased. As EV batteries age and their capacity diminishes, repurposing them for 2nd life applications offers substantial environmental and economic benefits. This approach reduces waste, conserves resources, and provides affordable Energy Storage Solutions (ESS). Aging is part of the operation of a battery, even during normal usage. Usually, there is a significant decrease of the nominal capacity during the first years of its operational life, which levels off afterwards. The average EV battery capacity loss is estimated to around 2.3% per year[2]. To ensure the optimal operational quality and driving range adequacy for the electric vehicle, most automotive industries offer a battery warranty of 7-10 years or driving range of 120,000- 160,000 kms[3]. Thus, at the end of the warranty, the expected EV battery nominal capacity varies between 70-80%. This is also the First-Life End-Of-Life (FL-EOL) threshold adopted by most automotive industries[4].

Even though such a battery does not fulfil the automotive requirements, its storage capacity can still be exploited for other applications. It is expected that over 5 million metric tons of EV batteries will be inappropriate for mobility purposes by 2030 [5]. This number is huge and reflects a great number of materials and storage capacity which will be useless to serve the mobility energy needs of the automotive industry. The cumulative capacity due to EV batteries after the end of their 1st life use is expected to increase to 185.5 GWh/year by 2025 and to 1000 GWh by 2030, offering a significant storage capacity for

2nd life applications[6]. Apart from passenger EVs, other types of vehicles and industrial motive machinery are getting electric in the transformation to green mobility and economy. The electric truck market is estimated to reach 1,067,985 units by 2030, while in 2022 it was 101,499 units. The electric construction equipment market is estimated to grow to USD 24.8 billion by 2027 from USD 9.2 billion in 2022. The demand for industrial motive batteries will reach ~50GWh by 2025[7]. These batteries, being much bigger than EV batteries, will offer significant capacity for exploitation at the end of their 1st life. In fact, there is a number of applications, where 2nd life batteries can be used, unlocking new revenue streams to different business stakeholders. Fourteen indicative 2nd life battery services for the electricity grid have been identified for the entire value chain of the energy system (i.e., end-user, utility, grid operator and off-grid) [8].

The environmental benefits due to re-using before recycling batteries are significant [9]. The re-use of the battery materials extends their lifecycle and reduce the need for new raw materials (ex. lithium, nickel, etc.) reducing, thus, the dependency of Europe from external resources. Furthermore, the energy consumption and carbon footprint of the construction process of a new battery is typically higher than the refurbishment of batteries.

The transition from the 1st life battery application to the 2nd life one is a challenging task since the BMS design between the 1st to 2nd life use implies different system, functional and safety requirements. Existing BMSes are customised to serve the functional and safety constraints of a specific technology and a specific application, and this is a hindering factor for the wider promotion of the 2nd life applications of batteries. For example, BMSes for automotive use are designed to serve the vehicle's mobility requirements and vehicle's auxiliary energy needs. For an efficient use in the 2nd life, the BMS must be adaptable to the requirements of the 2nd life operational application and ensure the safe and optimal performance of the new battery composed of its 2nd life modules. Furthermore, the power and energy requirements of 2nd life applications might require the combination of diverse battery technologies with different operational and technical specifications. This diversity may intensify as new technologies emerge in the future. There is a need for transitioning from a technology-driven rigid BMS to a data-driven, technology and application agnostic BMS.

2.2 Battery Management Approaches: Edge vs Cloud

The Battery Management System (BMS) is crucial for achieving maximum performance, safety, and longevity of battery systems. There are two main approaches to battery management: edge and cloud BMS [10]:

- **Edge battery management** is critical since it involves all the key functionalities requiring real-time (a few hundred msec) monitoring and decision making at local level to maintain the security and safety of the battery operation. The main advantage of this approach is that it ensures lower latency, lower costs and better security since the battery operational data are collected and processed locally. This approach requires increase storage capacity for tracking the hardware and software variant and increased computational resources in case more complex tasks or performant software features are adopted.

- **Cloud battery management** involves battery data collection at the edge, but complex processing and decision making is performed in the cloud. The key advantage of this approach is that the storage capacity and processing power are increased to support complex and demanding processes. The cloud-based processes can be applied in multiple battery applications offering scalability and cost-effectiveness. The challenges aspects of this approach are the higher latency and security risks, due to the edge-cloud interfacing for data transfer. In most cases, this introduces significantly higher costs as the necessary compute platform must be continuously available and able to support the whole fleet, while bandwidth costs can become excessive over time.

There are advantages and disadvantage as regards the deployment of one approach which highly depends on the application needs. The following table summarises the pros and the cons of the two approaches [10].

Table 1 Edge vs Cloud BMS: Pros and Cons

	Pros	Cons
Edge Battery Management	**Lower latency**: *Ideal for real-time processing with very low latency requirements.* **Reduced costs**: *Edge computing can help to reduce costs by offloading some of the processing to edge devices. This will also reduce the amount of data that needs to be transferred to the cloud. Computation and bandwidth are the main expenses with cloud computing, so this is a win on both fronts.*	**Complexity**: *Edge devices can be complex to manage. There might be a variety of edge devices and protocols deployed, and it can be difficult to keep track of everything and manage devices, hardware and software variants, etc.*
Cloud Battery Management	**Scalability:** *Cloud computing is highly scalable. If there is a significant increase in fleet size, or demand for processing power due to newly introduced features or a fleet wide analysis need – cloud resources can be easily scaled up to meet the increased demand.* **Cost-effectiveness for intermittent resource needs:** *Cloud computing can be cost-effective for applications that require a*	**Latency**: *Cloud computing can have high latency. This is because data needs to be transferred to and from the cloud, which can take time and will sometimes bear significant bandwidth costs.* **Connectivity needs:** *Always-on connectivity is required for certain functions relevant to operation and safety.*

	lot of processing power or access to substantial amounts of data intermittently. This is because cloud providers can amortize the cost of their infrastructure over many users which have variable demands. **Global reach:** *Cloud computing has a global reach. This means that users can be supported in any part of the world with monitoring, Over-The_Air (OTA) updates or fleet level analysis, etc.*	**Cost***: Both computation and bandwidth are expensive.*

A hybrid approach of cloud/edge BMS by combining the strengths of both edge and cloud computing seems to be the best alternative. A hybrid approach, combining both edge and cloud BMS, leverages the strengths of both systems. It offers low-latency computation for real-time diagnostics and prognostics at the edge while utilizing the cloud for advanced data analysis and scalability. The key benefits of this hybrid approach are:

- **Low-latency computation:** Edge BMS is necessary for real-time processing of the local battery data where low latency and high-frequency data is needed. Edge BMS serves critical diagnostic and prognostic functions.
- **Reduced costs:** A hybrid edge-cloud approach can reduce the costs of cloud computing by properly separating the edge/cloud functionalities to reduce the bandwidth costs and exploit optimally the computation resources at both levels.
- **Enhanced security:** Critical data for safety and security purposes can be kept at the edge BMS and only partial or historical data may be forwarded to the cloud BMS for evaluation purposes.
- **Scalability**: more advanced and complex functionalities can be performed at the cloud BMS due to higher computation and store capacity, whilst providing the flexibility to scale the analysis and decision-making in the field without affecting the computation executed in the edge.

Besides the positive aspects of the deployment of a hybrid BMS approach, there are challenges as well which need to the considered and mitigated. More specifically,

- **Data synchronisation**: Edge and cloud BMS should be synchronised to ensure that the decision making is performed based on up-to-date data. This means the communication channel between edge and cloud BMS needs to be reliable, secure and stable.
- **More complex management**: The hybrid edge-cloud BMS introduces additional complexity as regards management tasks. Handling the communication interfaces, user authorisation and accessibility to the data, execution and interfacing with cloud BMS processes, etc are tasks which introduce an additional burden.
- **Security**: edge and cloud BMS as well as all the communication links must be secure to protect sensitive data.

Co-funded by the European Union

2.3 Critical challenges towards open and interoperable BMS

Open-source and interoperable Battery Management System (BMS) design provokes unique challenges which are related to critical battery aspects, i.e. operational performance, safety, etc. The key challenges for developing an open and interoperable BMS include safety and reliability, communication interoperability, scalability, cell balancing, IP protection, and data governance. These challenges are discussed in detail below.

2.3.1 Safety and Reliability

A BMS comprises functions and sub-modules that ensure safe and reliable battery operation, extend battery life, and improve system performance. Key safety risks include over-voltage, thermal runaway, under-voltage, over-current, and under-temperature conditions. To mitigate these risks, a BMS must dynamically define Safe Operating Areas (SOA) and incorporate redundancy, partitioning, and failure detection mechanisms. Ensuring safety in open-source BMS designs requires rigorous testing and adherence to industry safety standards such as ISO 26262 and IEC 61508.

The measurement of battery variables such as cell voltage and temperature, battery current, etc. along with the detection and mitigation of SOA violations within a given timeframe are safety-critical tasks. Battery systems pose inherent safety risks – i.e. overcharging, over-discharging, thermal runaway, and short-circuiting.

Safety is critical in battery applications to avoid potential hazards as below:

- **Battery over-voltage:** Secondary chemical reactions triggered resulting in battery overheating, smoke emission, inflaming or explosion. It can be mitigated by precise voltage monitoring and control mechanisms.
- **Thermal runaway:** This can start a positive temperature feedback mechanism, with the same consequences as over-voltage. Effective thermal management and cooling systems are crucial for prevention.
- **Battery under-voltage:** This results in the progressive breakdown of electrode substances. Implementing lower voltage limits helps in avoiding this condition.
- **Battery over-current:** This may result in the melting of battery contactors, rendering them inoperable. Current limiting and protection circuits are essential.
- **Battery under-temperature**: This leads to the loss of robustness of contactors, reduced battery current capability, and dendrite formation. Proper thermal management and maintaining operational temperature ranges are important.

The primary goal of the BMS is to keep the battery cells within the SOA. These operational boundaries are defined by the battery manufacturers based on the operational properties of each specific battery chemistry. The safety operational area should be dynamically defined based on the storage application requirements. For instance, in a typical automotive and stationary storage application the long-term availability of the battery packs is critical, thus, the more sensitive settings for the SOA are adopted. On the contrary, in airborne applications, where in extreme cases the full availability of the system must be ensured, the operating area must be widened at the expense of batteries health state.

Safety measures - Passive and Active System:

- **Passive Safety**: Involves measures at both cell and system levels. At the cell level, the choice of cell chemistry directly influences safety.
- **Active Safety**: Includes individual cell voltage control, exact charge/discharge management, and temperature control/cooling systems. Monitoring of critical signals

Monitoring of critical signals

The monitoring of critical signals in a battery system is the key aspect to prevent potential hazards. All the BMS components for data acquisition, data processing and system control should be designed to serve the system safety requirements. **The main techniques to improve availability, robustness and reliability of the system are redundancy, partitioning and failure detection**. The development and certification of safety-critical applications is a costly process. In some cases, to reduce the costs, safety-critical components are encapsulated, and safety measures can hence be restricted to the respective parts.

Open and Interoperable BMS

An open and interoperable BMS should allow for straightforward integration of various safety strategies[12]. For example, FoxBMS adopts a safety-related method where safety-critical functions and diagnostics are implemented across different layers and hardware partitions. This approach includes different Master Control Units (MCUs) and diagnostics:

Primary MCU: Responsible for data acquisition and computations.

Secondary MCU: Independently checks the SOA of battery cells.

Isolated Interface: Facilitates diagnostics and data distribution between the two MCUs.

Three Levels of Diagnostics:

- BMS Diagnostics
- System Diagnostics
- System Consistency Checks

Redundancy, partitioning and diagnostic functions *aim to improve the safety integrity and reliability of a BMS.*

Ensuring the safety and reliability of an open-source BMS design requires rigorous testing, validation, and adherence to industry standards for functional safety such as ISO 26262, IEC61508, ISO13849, IEC 60730, IEC62619,62620,IEC63056 UN38.3,etc. Details on the functional safety framework designed and adopted in the Battery2Life project will be analysed and reported in the *B2L deliverable D2.1 "BMS functional safety design".*

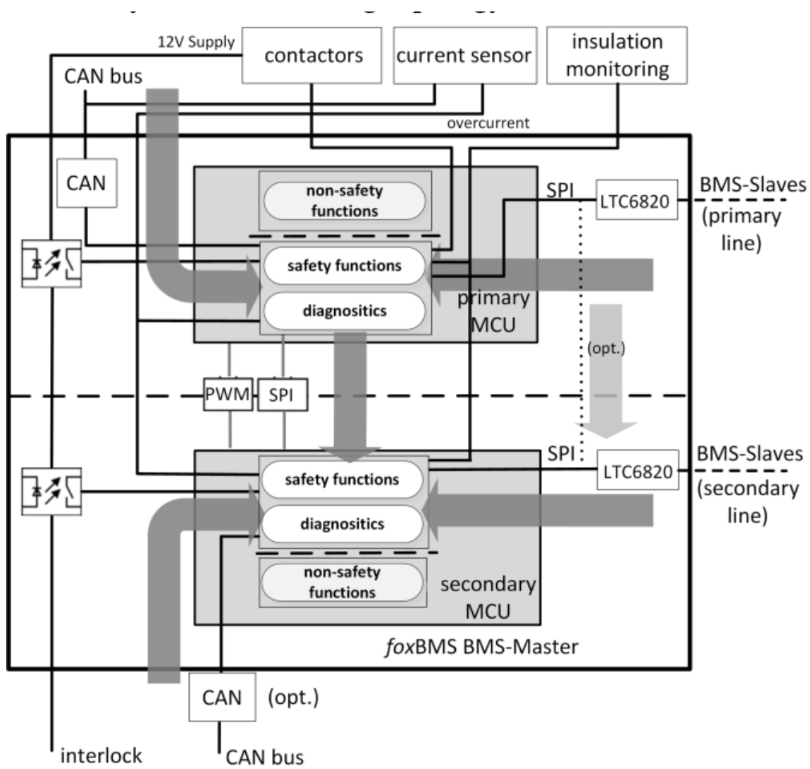

Figure 1 Redundant topology adopted by FoxBMS for safety and reliability [12]

2.3.2 Communication Interoperability

The BMS shall be equipped with a communication interface which acts as the communication channel between the BMS and third party systems for both 1st and 2nd life battery applications, ex. EV charging control unit, grid management system, battery inverter, etc. The key challenges of this communication interface are summarised below:

A BMS must be equipped with a communication interface to interact with third-party systems, such as EV charging units, grid management systems, and battery inverters, for both 1st and 2nd life applications. Key challenges include choosing the appropriate physical layer (wired or wireless), selecting suitable communication protocols (e.g., Controlled Area Network (CAN), ModBus), ensuring data structure compatibility, and maintaining security against unauthorized access. Achieving interoperability requires establishing common communication frameworks or developing software bridges to connect diverse systems.

There are some challenges that can be identified for these communication interfaces, summarised below:

- **Physical layer:** a wired or wireless communication can be established. In case of wired communication, Controller Area Network (CAN), Inter-Integrated Circuit (I2C), Serial Peripheral Interface (SPI), RS-485, and Universal Serial Bus (USB) can be a part of the physical layer of the communication interface. In case of wireless communication, Bluetooth, Wi-Fi, or cellular networks may also be employed in certain applications. The selection of the proper physical layer depends on the application requirements which might be different between 1st and 2nd life applications. Wireless communication is more convenient especially considering the 2nd battery life and disassembly process, however, there are some performance challenges which should be considered, i.e. lower data speeds compared to wired, less reliability and subject to interference.
- **Protocols:** Different communication protocols can be adopted on the top of the physical layer. Usually, CANopen, ModBus and System Management Bus are the most used protocols. In this project, for the communication between the edge and the cloud BMS, internet-based protocols should be considered such as Message Queuing Telemetry Transport (MQTT) or Hypertext Transfer Protocol (HTTP)/HTTPS.
- **Data structure:** Information such as the battery voltage, current, temperature, SoC, SoH, is transmitted via the BMS to the cloud BMS. Depending on the communication protocol being used, these data points may be arranged in certain structures or data frames.
- **Security:** The security of the communication interface is critical and unauthorised access to the BMS should be prevented. In this respect, the communication between the cloud and the edge BMS should be secured adopting authentication procedures data encryption and other cybersecurity measures.
- **Interoperability:** The BMS may need to connect with different system between 1st and 2nd life applications which may employ diverse communication technologies and protocols. To achieve openness and interoperability a common communication framework needs to be established or proper software bridges, gateways or protocol converters shall be developed to bridge these gaps.

In order to choose the best communication protocol for a Battery Management System (BMS), it is important to carefully consider a number of factors [13]. This procedure is crucial since the selected protocol affects the system's overall effectiveness, efficacy, and cost. Data Rate is the first critical factor which describes the amount of data that can be transported in a given amount of time. For applications that demand regular or real-time updates, such as monitoring battery performance in an electric car, high data rates are advantageous.

High data rates are provided by protocols like Ethernet, although they could be overkill for smaller applications with infrequent communication requirements. Reliability and noise Immunity are critical to sustain precise and reliable communication in the presence of noise or interference. Power consumption is an important factor to consider especially for battery-powered devices or applications that require low energy consumption. Finally, a balance between costs and performance should be considered.

A communication protocol's expenses can be attributed to a number of factors, such as hardware parts (such as transceivers), software license (if necessary), development time, and maintenance. High-end protocols could perform better, but they might also be too expensive for some applications. To choose a protocol that provides the required functionality at an acceptable cost, cost and performance must be balanced.

2.3.3 Scalability

The power and energy requirements for battery systems vary widely depending on the battery application needs. In grid and residential Energy Storage Systems (ESSs), the system complexity increases as the number of connected cells increased and by a possible 2nd life use of used/aged cells. Designing an open-source BMS that is scalable across different applications and battery chemistries requires flexible [14] - [15].

Centralized BMS topologies

In this case, all functionality is integrated into a single module connected to batteries via wires, present significant scalability challenges. The limitations include:

- **Single-Point Failures**: A fault in the centralized module can compromise the entire system.
- **Wiring Complexity**: As the number of cells increases, so does the complexity and length of wiring, leading to potential signal integrity issues and increased installation difficulty.
- **Fixed Capacity**: The maximum number of batteries is strictly predefined, limiting scalability. Additionally, only predefined single battery technologies are supported.

Modular and Distributed BMS Topologies

Adopting modular and distributed BMS topologies can overcome these challenges. Decentralized architectures bring functional units closer to individual cells or modules, enhancing scalability and reducing the impact of single-point failures. These approaches require advanced balancing algorithms but enable more flexible and resilient system designs. Key advantages include:

- **Enhanced Scalability**: Functional units can be added or removed as needed, accommodating various system sizes and configurations.
- **Improved Reliability**: Decentralized units act independently, so the failure of one unit has a minor impact on the overall system.

- **Flexibility**: Supports multiple battery technologies and configurations, making it adaptable to different applications and chemistries.

Central Master-Slave BMS Approach

In a central master-slave BMS approach, scalability is limited:

- **Predefined Capacity**: The maximum number of batteries and supported technologies are fixed.
- **Hardware Intensive**: Grid or utility-scale applications require multiple battery packs operating in parallel, necessitating a separate pack management system as a master and individual BMSs in each pack as slaves. This dependency on the master's capacity restricts the number of parallel battery packs.

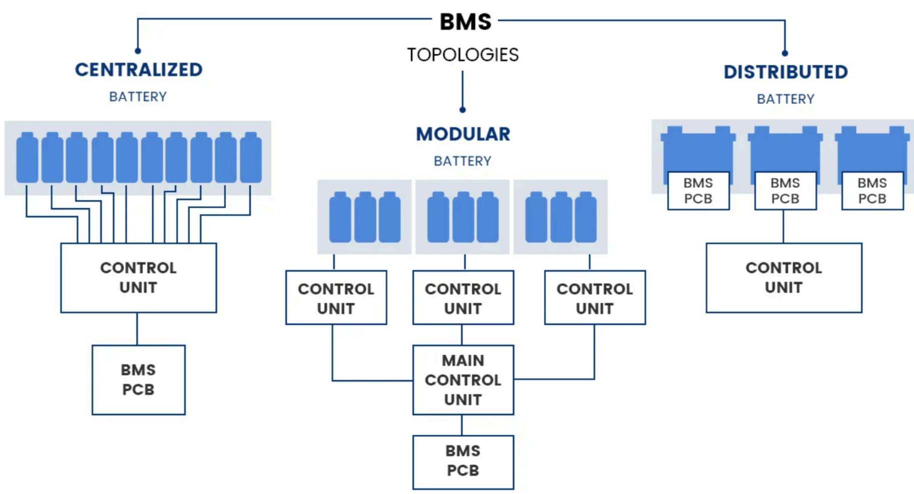

Figure 2 Different BMS topologies towards scalability [16]

Distributed, Modular, and Hybrid BMS Topologies

Adopting distributed, modular, or hybrid BMS topologies can significantly enhance scalability. These topologies decentralize the architecture, positioning functional units closer to the battery/cell, allowing them to act independently:

- **Decentralized Operation**: Functional units operate independently of a central coordinator. Failure of a single unit has a minimal impact on overall system performance.
- **Advanced Balancing Algorithms**: These topologies require more sophisticated algorithms to manage balancing and ensure uniform performance across the system.

More detailed analysis on the BMS topology has been performed in D1.3 "*BMS specifications and advanced algorithms for 2nd life*".

2.3.4 Cell balancing

If the type of cell or configuration changes the following parameters must be adapted or checked to provide proper functionality of the active balancing:

- **Nominal cell capacity** - Always verify the nominal capacity of new cells and update the BMS configuration accordingly. Incorrect capacity settings can lead to improper balancing and reduced battery performance.
- **Maximum allowed balancing current** (based on the datasheet of the new cell which should be balanced) - Ensure the balancing current does not exceed the cell's discharge limits. This protects the cells from potential damage due to overcurrent.
- **Series Configuration Management**: When dealing with a large number of cells, plan for the integration of multiple MMS units. Ensure the BMS software is capable of managing multiple MMS units to maintain efficient balancing.
- **Continuous Monitoring and Testing**: Regularly monitor the balancing process and test the system after any configuration changes to ensure all parameters are correctly set and functioning as expected.
- **Maximum Allowed Balancing Difference**: Set the balancing difference to appropriate levels to avoid under or overcharging individual cells. This helps in maintaining the overall health and longevity of the battery pack.

The maximum allowed balancing current must not exceed the maximum allowed discharge current of the cell. If necessary, the balancing current must be changed by replacing the R_{Iset} resistor at the MMS hardware. The before mentioned parameters must be known to calculate the maximum allowed balancing time.

There is a maximum number of cells in series that a single MMS could handle. If more cells in series are needed, then multiple MMS PCBs must be used.

2.3.5 IP protection for SoX estimators in Open-source BMS

Making a Battery Management System (BMS) software stack open-source while protecting key intellectual property (IP) related to State of Charge (SoC) and State of Health (SoH) estimators involves several challenges. To effectively safeguard IP, protection must be ensured at three levels: the open-source repository, during the adaptation/reconfiguration process, and when deployed on the BMS hardware (secured against reverse engineering).

2.3.5.1 Key Measures for IP Protection

I. **Cleanly Structured Repositories with Protected Submodules**

Ensure a clear separation between open-source and proprietary components by organizing repositories cleanly. Sensitive SoX algorithms and proprietary code should be housed in protected submodules, accessible only to authorized users.

II. **State-of-the-Art Cybersecurity for Data Exchange**

Implement robust cybersecurity measures to protect data exchanged between the cloud and the battery system. This includes encryption, secure communication protocols, and regular security audits to prevent unauthorized access and data breaches.

III. **Secure Deployment Environments**

Protect executables against reverse engineering by using techniques such as code obfuscation, secure enclaves, and hardware-based security modules. These measures ensure that the deployed environment remains secure.

IV. **Use of Precompiled Libraries with Clear Documentation**

Distribute precompiled libraries instead of source code for critical SoX components. This prevents unauthorized modifications and reverse engineering. Provide clear documentation and block diagrams to help third parties understand and integrate the functionality without exposing the underlying IP.

V. **Sufficient Tooling and Documentation**

Provide comprehensive tooling and documentation to ensure the open-source repository is easily usable by third parties. Include tutorials, API references, and example configurations to facilitate understanding and integration without compromising proprietary aspects of the SoX estimators.

2.3.5.2 Recommendations for Enhancing IP Protection

I. **Repository Structure**

Clearly document the repository structure and access controls to help third parties understand which parts are open-source and which are protected. Use version control systems with fine-grained access permissions to further enhance security.

II. **Regular Cybersecurity Updates**

Regularly update cybersecurity protocols and practices to address emerging threats. Incorporate multi-factor authentication (MFA) and role-based access control (RBAC) to further secure the system.

III. **Advanced Deployment Security**

Explore advanced techniques like binary signing, secure boot, and runtime application self-protection (RASP) to fortify the security of deployed executables.

IV. **Comprehensive Documentation and Visualization**

Develop detailed block diagrams and flowcharts that illustrate the functioning of precompiled libraries. This helps third parties understand the system architecture and integrate the BMS without accessing sensitive code.

Community Engagement

Engage with the open-source community to foster collaboration while maintaining IP protection. Offer limited access to certain proprietary features under specific licenses or agreements.

2.3.6 Battery Digital passport & Data governance

The EU Battery Regulation 2023/1542 is the first regulatory initiative covering the whole product life cycle of batteries. It details the requirements for transparency on carbon footprint, including performance classes and maximum threshold values, metal-specific recycling rates, recycled content quotas, corporate supply chain due diligence obligations, minimum requirements for durability and performance, as well as the introduction of a digital battery passport – the first Digital Product Passport (DPP) at the European level [18]. The digital battery passport is analysed in Chapter IX of the EU Battery Regulation and will be mandatory from 18th of February 2027 for batteries in several application including electric vehicle batteries.

The digital battery passport aims to support the sustainable and circular management of batteries. In this respect, comprehensive data along the entire battery value chain needs to be collected, documented and exchanged via a digital infrastructure. Currently, there is no final definition of the digital battery passport and the respective European Commission services have not been established. In this respect, there are no specific guidelines to be deployed for the battery passport unless new standards are established. However, there are some initiatives aiming to pave the way towards a holistic digital battery passport, such as Battery Pass project [18], the Global Battery Alliance (GBA) battery passport [19]. The Battery2Life project aims to focus on the definition of the necessary battery data (static or dynamic) that are useful for the evaluation of the battery for 2nd life application (D2.3 *"BMS cloud platform*)". Irrespectively of the final definition of the digital battery passport, the most critical challenge to address is the distributed information exchange of potentially highly sensitive data among various stakeholders, end users, business partners from diverse sectors, authorities etc. These communication interfaces must be secure and reliable and should conform to different standards and protocols. At the battery level, it is expected that different communication protocols might exist but as the information is shared with more central entities (i.e. third-party product passport service providers, EC service, etc.) dedicated standards at EU level should be established.

The way towards digital passport deployment has many challenges to be addressed [20]:

- **Technical and system challenges**
  - *Unavailability of harmonised standards. CEN/CEMELEC are working towards this direction*
  - *Lack of reliable, interoperable infrastructure*
  - *Inefficiencies in handling large data volumes*
  - *Complexity of integrating data into existing systems*
  - *Limited access to crucial IT resources*
- **Data accuracy security challenges**
  - *Lack of audit processes*
  - *Insufficient data quality, lacking reliability*
  - *Data inconsistencies and contradictions*
  - *Lack of concrete security measures*
  - *Risk of intellectual property rights infringement*
  - *Exposure to unauthorised access risks*
  - *Concerns about privacy and security of personal data*
- **Data sharing and p2p agreements**
  - *Missing of data-sharing agreements*
  - *Limited trust among stakeholders*
- **Capacity building challenges**
  - *Lack of experience and know-how from involved stakeholders*
  - *Time margins for training are needed*
- **Regulatory challenges**
  - *New EU Battery Regulation 2023/1542*
  - *Revision of existing standards is needed with respect to the new regulation*

The deployment of a hybrid cloud/edge BMS raises new challenges as regards the cloud data governance. This comprises the proper set of processes that ensures that battery-related data stored in cloud BMS is secure, accurate, and compliant with all relevant data privacy regulations and policies. It also frames the accessibility rules from different stakeholders to the different battery data.

Data quality and integrity are primary goals for data governance to ensure that data is accurate and consistent across all BMS levels. The granularity of the BMS data differs based on the use cases. The outcomes of the battery state estimators can be stored in a daily, weekly or monthly basis since any deviation is expected to be released in long term periods. On the contrary, if any abnormal operational measurement is extracted, then battery measurement such as voltages/currents/temperature at pack and/or cell level at very small intervals (<0.5sec) might be needed to evaluate the battery operational conditions. The data granularity should be adjustable to support both battery assessment needs.

The data collected and stored in the cloud BMS should conform to the requirements dictated by the directive for the battery digital passport [17]. The deployment of a hybrid BMS approach and the aggregation and processing of the battery data at the cloud BMS facilitates the regulatory compliance in a homogeneous way irrespectively of the battery application.

3 B2L BMS APPROACH

3.1 B2L business pillars

The project aims to develop two BMS solutions in order to serve two different business objectives or pillars:

- ***Pillar 1 - industrial load levelling application to support electromobility***

  The scope of this business use case is to assess the exploitation of the 2nd-life stationary storage energy systems for grid-scale application towards enabling a more efficient integration of EVs into the electricity grids. More specifically, this case is a very appealing path to ensure the efficient integration of fast-charging infrastructure in the weak electricity grids of islands. Envisioning the adoption of this business use case is the future of green e-mobility charging hubs, where several charging infrastructures supporting different charging levels (from 22 kW up to > 150 KVA) will serve the needs of different vehicle types simultaneously, which integrates both renewable and 2nd life storage solutions to minimise their environmental footprint and grid impact. The synergetic operation of charging infrastructures and Renewable Energy Sources (RES) aims to contribute to the decarbonisation of the transport sector by enabling green charging even when charging demand and RES production do not coincide by exploiting the storage capacity of 2nd life batteries. Furthermore, since the charging power of such charging hubs will impose additional burden to the electricity grid, especially in the case of high-power chargers, the 2nd life storage can be exploited to shave demand peak shaving and relieve the grid pressure.

- ***Pillar 2 - Domestic storage application to facilitate self-consumption for prosumers***

The second business use case focuses on domestic home storage applications. The green energy transition and the ambitious targets as regards the RES shares in the electricity grids dictates the introduction of significant amounts of battery storage capacity to ensure the equilibrium between production and consumption. Furthermore, the increasing electricity prices and the low feed-in remuneration of the photovoltaic (PV) generation from the prosumers implies the importance of self-consumption practises for the amortisation of the residential PV systems.

3.2 Hybrid BMS architecture

The component architecture for the hybrid BMS approach in the project is illustrated in the following figure. More specifically,

- The **blue boxes** define the processes which are related to the processing, storage, accessing of data which are sourced from the edge BMS. The blue boxes are in-built modules that offer vendor -gnostic services for data collection.
- The **grey boxes** define the processes which are needed for handling data which are provided by external resources, ex. battery specifications which might will be provided by the battery Original Equipment Manufacturer (OEM) based on unified template via the user interface or data related to the forecasted battery operational profiles under specific business applications.
- The **red boxes** define the battery-related services (SoX estimators) which will be developed within the Battery2Life project and can be implemented either at cloud or edge BMS level.
- The **yellow boxes** define the communication interfaces that needs to be established to allow data information between the edge- and cloud- BMS as well as between cloud-based BMS processes and the BMS cloud.

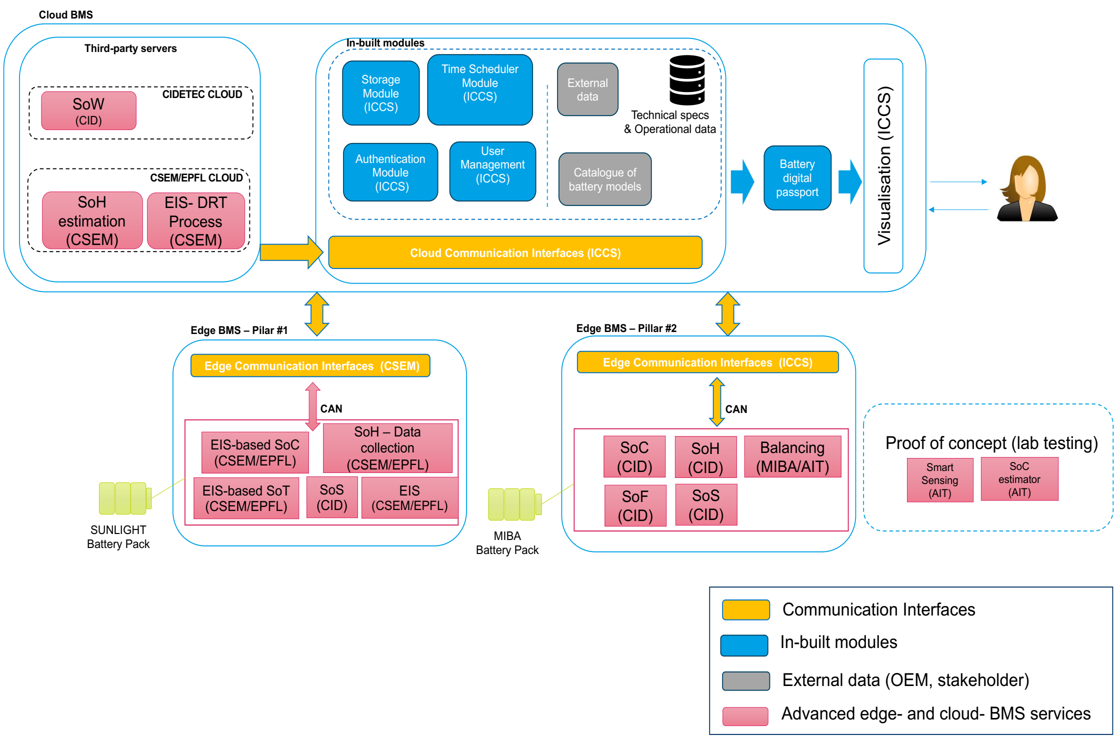

Figure 3 Component architecture for the B2L hybrid BMS

The cloud BMS processes (red boxes) can be executed either in the same cloud server where the BMS is operated or in third party cloud servers implemented by the service providers. Proper interfaces and APIs will be developed to enable the data exchange between the cloud BMS database and the BMS processes.

The in-build modules of the BMS clouds are:

- **Authentication module**: responsible for providing access to cloud resources to identified users.

- **User management module**: responsible for registering accounts to the platform and managing user accounts
- **Storage module:** database module that stores all the necessary information and data
- **Time scheduler module**: provides the functionality of scheduling a suitable time period in which different processes will be executed

In regards to the SoX estimators the specifications of the algorithms are presented in detail in B2L deliverable D1.3 “*BMS specifications and advanced algorithms for 2nd life*”. In the following paragraphs the specification for the cloud-edge communication for the realisation of the SoX estimators will be presented.

3.3 BMS functions - State machine diagrams

The scope of this section is to provide the state machine diagrams for the different BMS processes implemented in each project pillar. The detailed specifications of each BMS process will be analysed in B2L deliverable D1.3 "*BMS specifications and advanced algorithms for 2nd life*".

3.3.0 Pillar 1: Industrial load levelling application

The high-level state machine diagram for the BMS in the business pillar 1 is illustrated in the following figure.

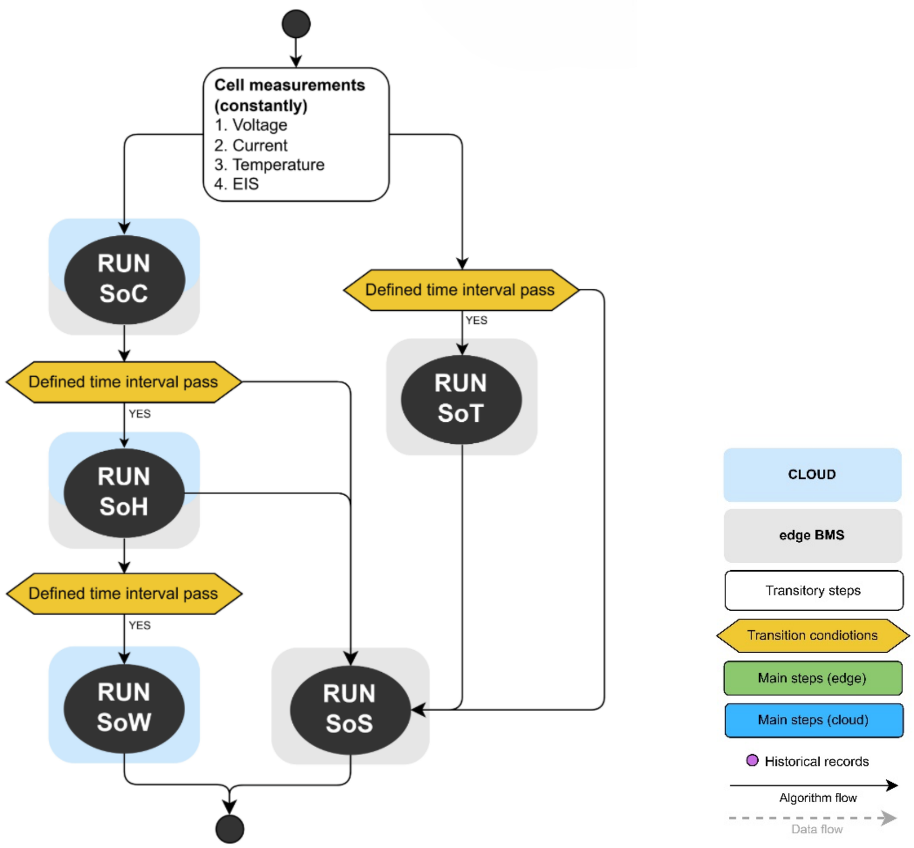

Figure 4 High-level BMS state machine diagram (Pillar 1)

In Pillar 1, voltage, current, temperature and EIS measurements at cell level will be continuously monitored. At the same time, the SoC estimation will be updated, while the Equivalent Circuit Model (ECM) parameters for the SoC estimator will be periodically updated in the cloud. Once the SoC is updated, the SoH can also be updated, a periodic action for which specific time interval will be defined. The SoH will mainly run in the cloud, but measurements will be performed locally on the edge. The SoW will run periodically and will take into account the SoH as input. In parallel, whenever the defined time interval has elapsed, the SoT will be run on the edge BMS and updated. Finally, the SoS will be executed by constantly defining security limits, or by periodically defining alerts for security issues.

3.3.0.3 EIS-based SoC estimator

The EIS-based SoC shall partially run on the edge-BMS and in the cloud. The model-based SoC estimation (at cell level) will be constantly updated in the edge-BMS based on cell voltage and current measurements. In addition, periodic EIS measurements will need to be transmitted to the cloud for DRT (distribution of relaxation time) analysis and subsequent ECM (equivalent circuit model) parameter tuning. Moreover, the SoC estimation and ECM parameters will be stored in the cloud database (DB) for historical records.

The EIS module at the edge BMS communicated periodically to the cloud BMS the EIS measurements which is an array with the following parameters:

Ffrequency
- *Z_RE, Z_im, Z_mod, Z_phz*
- *Voltage*

The records from the EIS module are stored in the database of the cloud BMS and they are accessible by the EIS-DRT service via a respective Application Programming Interface (API). The outcomes of the EIS-DRT will be forwarded to the cloud BMS to be stored and to be forwarded to the edge BMS to update the EIS configuration parameters:

- *Voltage*
- *R0, R1, R2, R3, R4*
- *C1, C2, C3, C4*

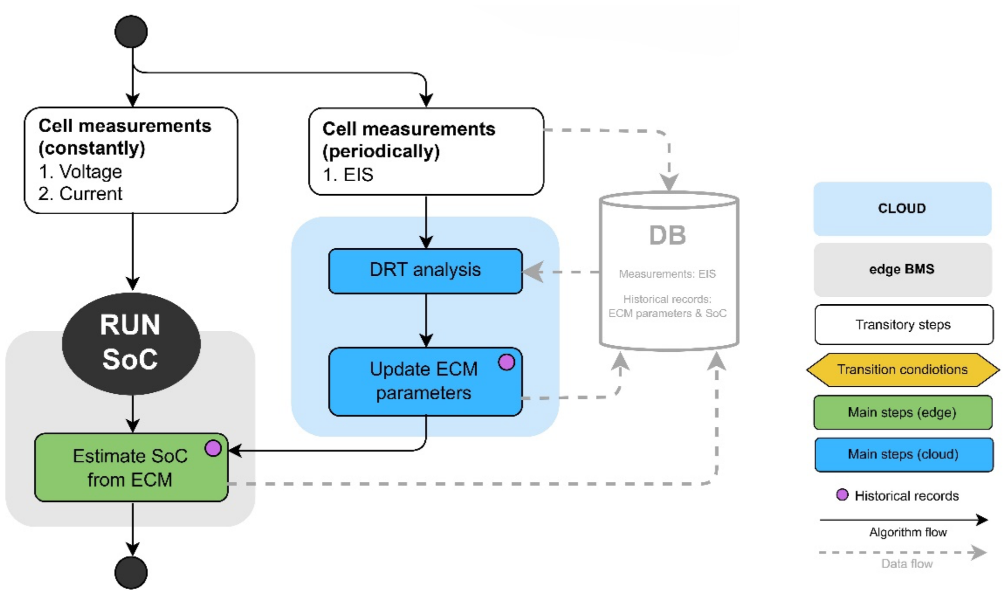

Figure 5 EIS-based SoC state machine diagram (Pillar 1)

3.3.0.4 EIS-based SoT estimator

The SoT estimation at cell level will be executed in the edge-BMS periodically, based on a defined time interval. The estimation is performed by phase-shift analysis of the EIS measurements. The estimation will be shared with the cloud and stored in the DB for historical records.

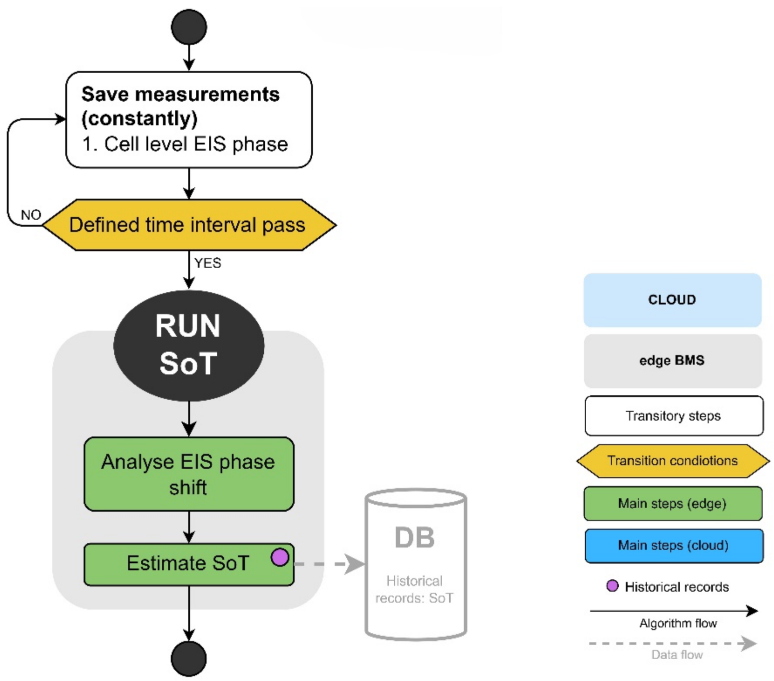

Figure 6 EIS-based SoT state machine diagram (Pillar 1)

3.3.0.5 SoH estimator

The cell SoH estimation will be a differential capacitance study based on dQ/dV and Coulomb counter. Although the necessary measurements will be collected locally, the estimation will be performed in the cloud periodically, based on a defined time interval which could be a week or a month. The cell voltage and current measurements will be sent to the cloud and stored in the DB for later analysis. The accumulated cell voltage and current values will be analysed first by a Coulomb counter to estimate the charged and discharged capacity, and then by a dQ/dV analysis to assess degradation. This will define the SoH of the cell. Subsequently, new operating power limits will be defined based on the updated battery capacity. In addition, a historical record of the SoH estimation will be carried out.

As an input, the SoH algorithm requires cell voltage measurements as well as the SoC measurements. Thus, the data to be collected and communicated at the edge BMS are:

Co-funded by the European Union

- *Cell voltage*
- *Cell current*
- *SoC*

The output of the SoH algorithm is the state of health at cell or module level which should be stored in the cloud database for further processing and analysis.

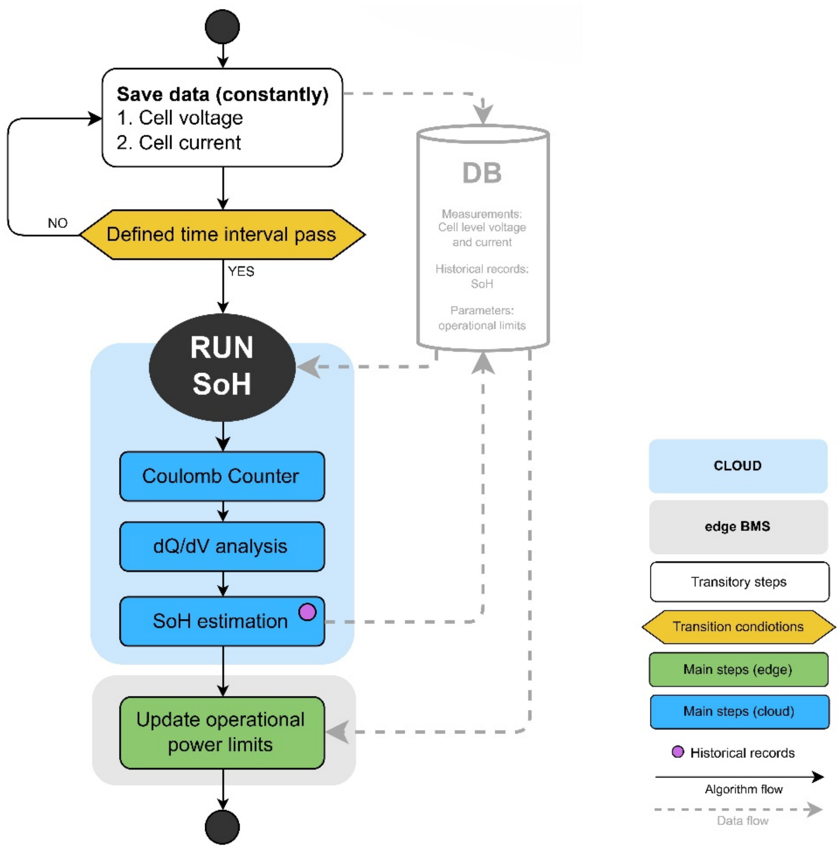

Figure 7 SoH state machine diagram (Pillar 1)

3.3.0.6 SoW estimator

The SoW, as a multiple maintenance approach, will be defined according to different maintenance factors: Remaining Warranty (RW), Remaining Health (RH) and Remaining Useful Warranty (RUW). For this purpose, the SoH and discharged Ah values will be stored in the cloud DB. Every time the defined time interval passes, the SoW will be executed by first reading the necessary information, and then estimating the different maintenance factors. Then the SoW can be estimated. This estimator will be run in the cloud periodically and stored in the DB for historical records as well as additional maintenance factors.

The parameters extracted by the diagnostic-sizing tool, detailed in D1.3 "*BMS specifications and advanced algorithms for 2nd life*", as well as the latest record from the SoH estimator will be introduced to the SoW algorithm for the calculation of the state-of-warranty of each cell. These parameters which are summarised below are referring to the 2nd life application and they should be stored in the cloud BMS database with a timestamp. The latest record from the results of the sizing tool should be used by the SoW estimator.

Parameter	Description
• SoC_{max}	*Maximum allowable value for SoC*
• SoC_{min}	*Minimum allowable value for SoC*
• FEC_{day}	*Number of full equivalent cycles per day*
• SoH_{EoL}	*State of health considering at the end of life*
• $*E_{nominal}$	*Nominal energy capacity*
• $*I_{ch\_max}$	*Maximum charging current*
• $*I_{ch\_std}$	*Maximum charging current suggested to be used*
• $*I_{dch\_max}$	*Maximum discharging current*
• $*I_{dch\_mean}$	*Mean value of discharging current*
• $Lifespan_{years}$	*Battery lifespan in years*
• $Lifespan_{FEC}$	*Battery lifespan in full equivalent cycles*
• N_{cells_mod}	*Number of cells per module*
• $N_{modules}$	*Number of modules*
• *OEM_ID*	*Manufacturer*
• *System_ID*	*Unique identity of system under study*
• *Project_ID*	*Unique identity of project under study*
• $*T_{avg}$	*Average temperature*
• $*T_{max}$	*Maximum value of temperature*
• $*T_{min}$	*Minimum value of temperature*
• *xh0*	*Parameter for the mathematical representation of the SoH evolution*
• $SoH_{evolution}$	*State of health evolution with respect to the* $Time_{Evolution}$
• $FEC_{evolution}$	*Full equivalent cycles evolution with respect to the* $Time_{Evolution}$
• $Time_{Evolution}$	*Time period*

The output of the SoW estimator is a set of four parameters detailed in as follows:

- *State of warranty with a colour indicator as illustrated below.*
- *The remaining warranty (RW) for the reactive maintenance.*
- *The remaining health (RH) for the preventive maintenance.*
- *The remaining useful warranty (RUW) for the predictive maintenance.*

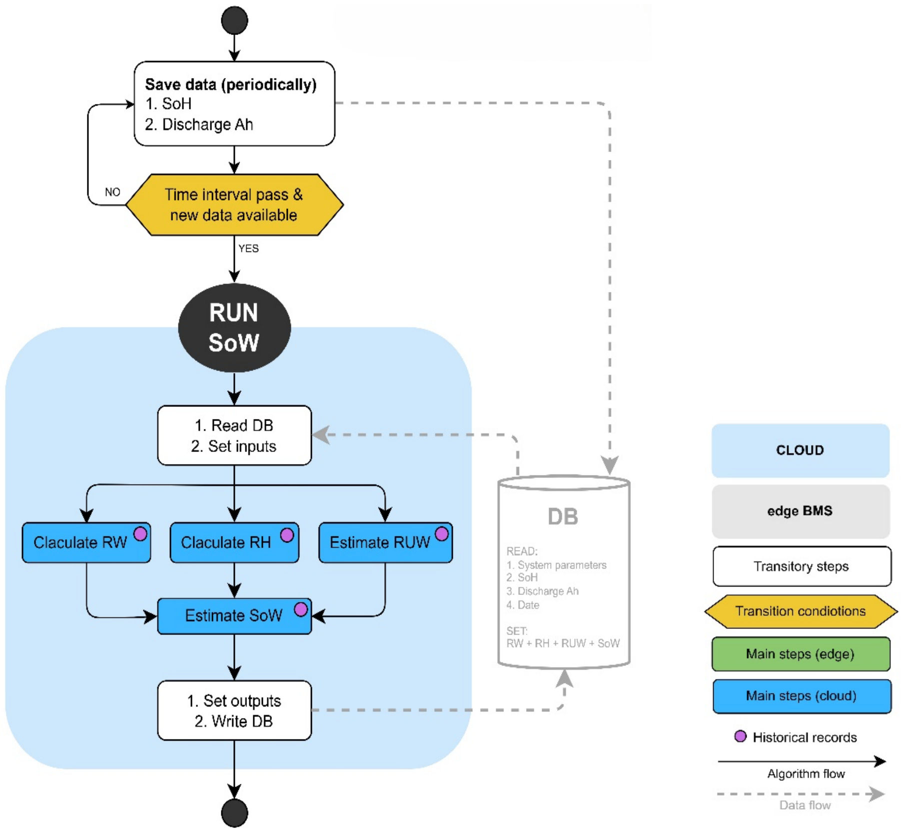

Figure 8 SoW state machine diagram (Pillar 1)

SOW	*RW*	*RH*	*RUW*	*Severity Description*
	>0.05	*>0.75*	*>0.5*	*The warranty fulfilment level is correct.*
	<0.05	*>0.75*	*>0.5*	*The warranty fulfilment level is correct, but the end of warranty is close.*
	-	*>0.75*	*0.5> RUW >0.4*	***ATTENTION**! Predicted 1 additional replacement. Early advice.*
	-	*0.75>RH>0.5*	*0.5> RUW >0.4*	***ATTENTION**! Predicted 1 additional replacement. Middle advice.*
	-	*0.75>RH>0.5*	*0.4> RUW >0*	***ATTENTION**! Predicted 1 additional replacement. Late advice.*
	-	*0.5>RH>0*	*0.4> RUW >0*	***DANGER**! Predicted 1 additional replacement. Irreversible damages.*
	-	*-*	*0*	***DANGER**! Predicted 2 additional replacement.*
	-	*0*	*-*	***DEATH**! The battery has reached the EOL.*
	¿?	*¿?*	*¿?*	***Undefined scenario.** Something unexpected is happening.*

Figure 9: Qualitative states of SoW

3.3.0.7 EIS-based SoS estimator

For Pillar 1, the SoS will be an EIS-based approach. On the one hand, the safety limits shall be constantly defined depending on voltage, current, temperature and EIS (both magnitude and phase) measurements at cell level. On the other hand, the thermal runaway warning will be defined periodically, if necessary, based on EIS. The SoT will also be considered as input for algorithm reinforcement, as this will add valuable indicators of which cells may be closer to the TRA. In this way, the safety level can be estimated and the SoS indicator can be updated. This indicator will be defined at cell level and stored in the cloud DB for historical records.

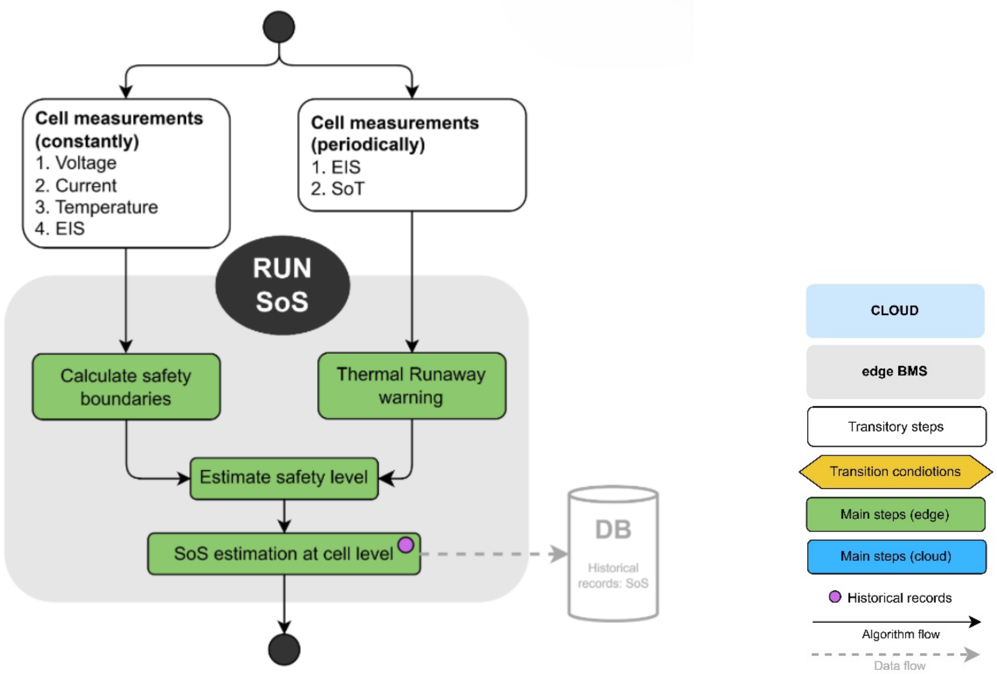

Figure 10 EIS-based SoS state machine diagram (Pillar 1)

3.3.1 Pillar 2: Domestic storage application

In the case of Pillar 2, cell level measurements will also be carried out, although there will be no EIS monitoring, but voltage, current and temperature measurements. Based on these measurements, an estimation of the SoC will be constantly performed. During charging, the State of Function (SoF) will limit the charging current according to safety limits. During resting mode, on the one hand the SoS will be updated, and on the other hand, and only after the defined time interval has elapsed, the SoH will be updated, as well as the SoW, which in this case will be the only estimator running in the cloud. In addition, whenever cell balancing is requested, active balancing will be performed.

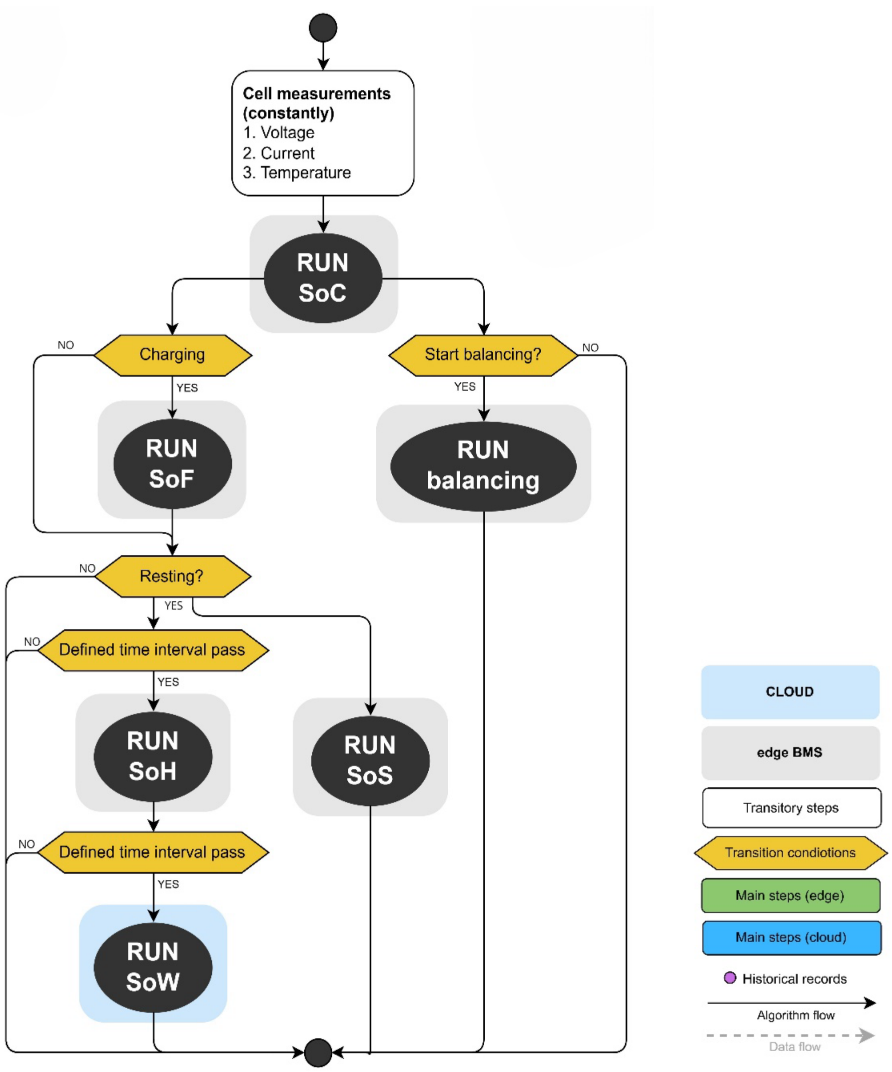

Figure 11 High-level BMS state machine diagram (Pillar 2)

3.3.1.8 SoC estimator

The SoC will be estimated in three steps. First, the ECM-based SoC will be defined, which will then be corrected by the Extended Kalman Filter (EKF) in a second step. Finally, cell level SoC estimation will be defined by combination of both and stored in the cloud DB. For this estimation, constant voltage, current and temperature measurements at cell level will be necessary.

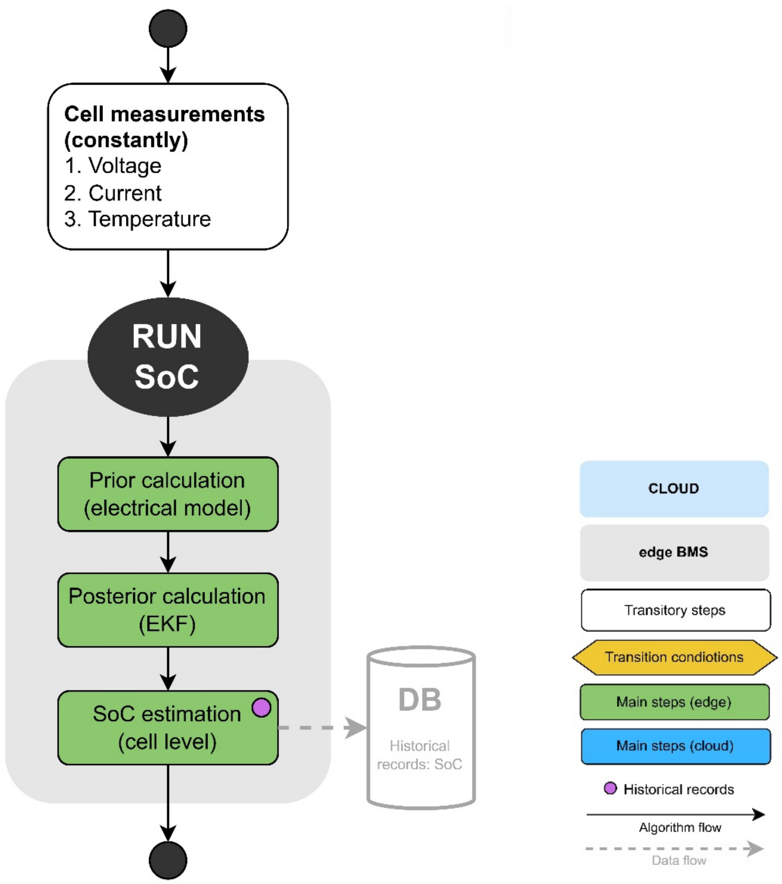

Figure 12 SoC state machine diagram (Pillar 2)

3.3.1.9 SoH estimator

To estimate the SoH at the cell level, it is first necessary to estimate the SoC, which in turn requires cell level measurements. During the charging period it will be necessary to measure cell voltage, current and temperature, while at resting there will be no current and only voltage and temperature will be analysed. Although the SoC is constantly updated, the SoH will be executed once the charging is finished and a defined time interval has elapsed. The accumulated SoC values will be analysed to assess the degradation in order to be able to update the SoH. At the same time, historical records of the SoH will be kept in the DB.

The information exchange between the edge/cloud BMS for the SoH estimator is the same as in pillar 1.

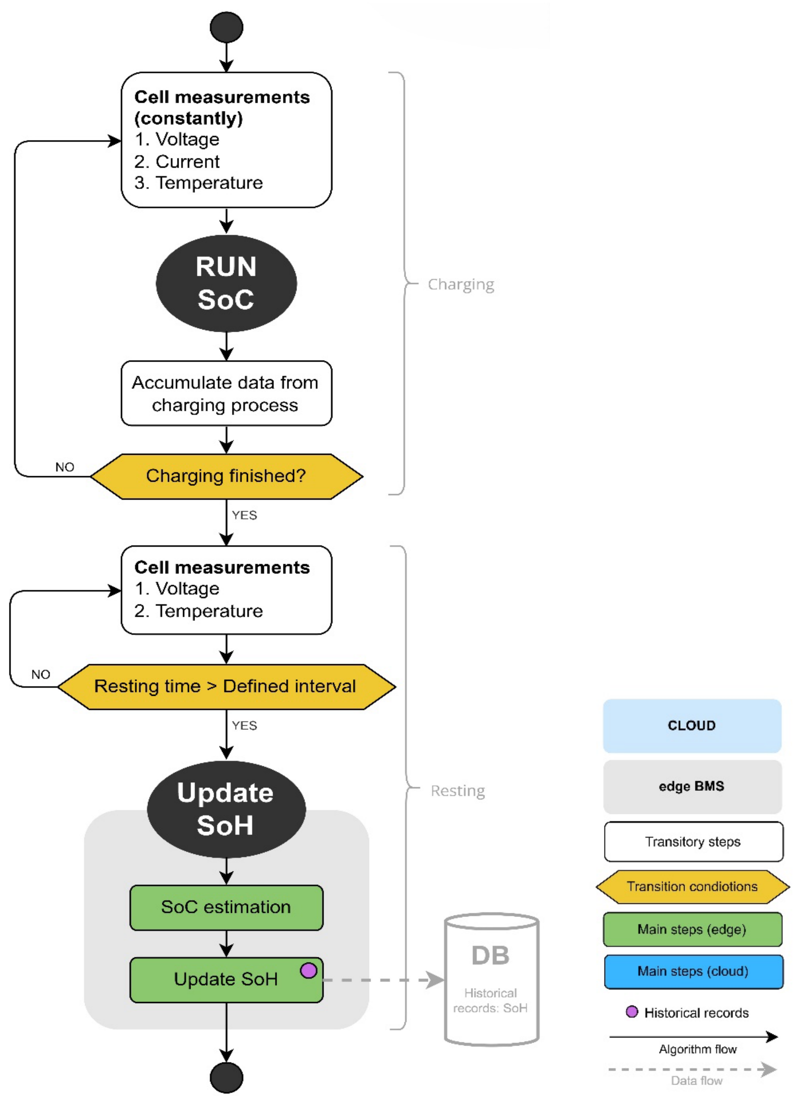

Figure 13 SoH state machine diagram (Pillar 2)

3.3.1.10 SoF based SoS estimator

The SoS approach for Pillar 2 is actually composed of two estimators, which are the SoF and the SoS. The SoF will ensure the safety limits during charging process, and the SoS will be updated during resting time. The SoF will limit the charging current based on operating conditions which are cell level measurements (voltage, current and temperature) and SoC value, which will be updated beforehand. The SoF bases on a look-up table which has been defined to avoid unsafe operation conditions and will limit the current. The SoS will be updated based on the analysis of the dV/dt curves which, at the same time, need cell level voltage and temperature measurements. Once resting time exceeds a defined time interval, and lithium-plating is detected from the dV/dt curves, the SoS indicator is updated. This estimator will be stored in the could DB for historical records, not as SoF which is simply a current limiter.

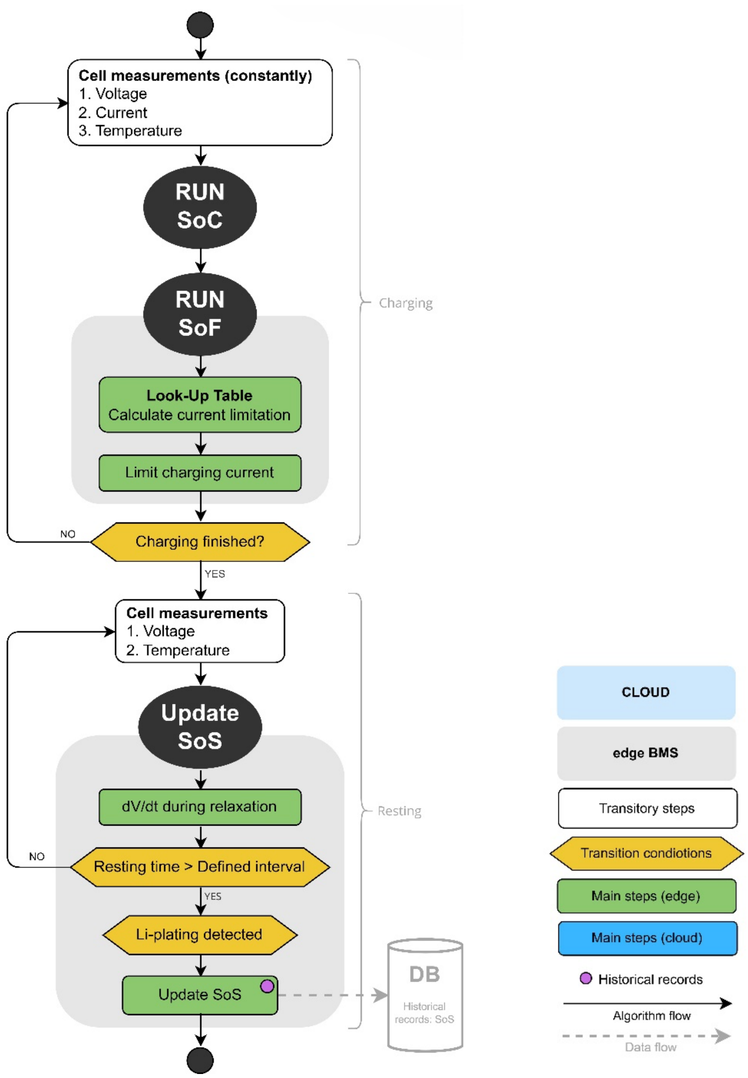

Figure 14 SoF based SoS state machine diagram (Pillar 2)

3.3.1.11 SoW estimator

The SoW, as a multiple maintenance approach, will be defined according to different maintenance factors: RW (remaining warranty), RH (remaining health) and RUW (remaining useful warranty). For this purpose, the SoH and discharged Ah values will be stored in the cloud DB. Every time the defined time interval passes, the SoW will be executed by first reading the necessary information, and then estimating the different maintenance factors. Then the SoW can be estimated. This estimator will be run in the cloud periodically and stored in the DB for historical records as well as additional maintenance factors.

The information exchange between the edge/cloud BMS for the SoW estimator is the same as in pillar 1.

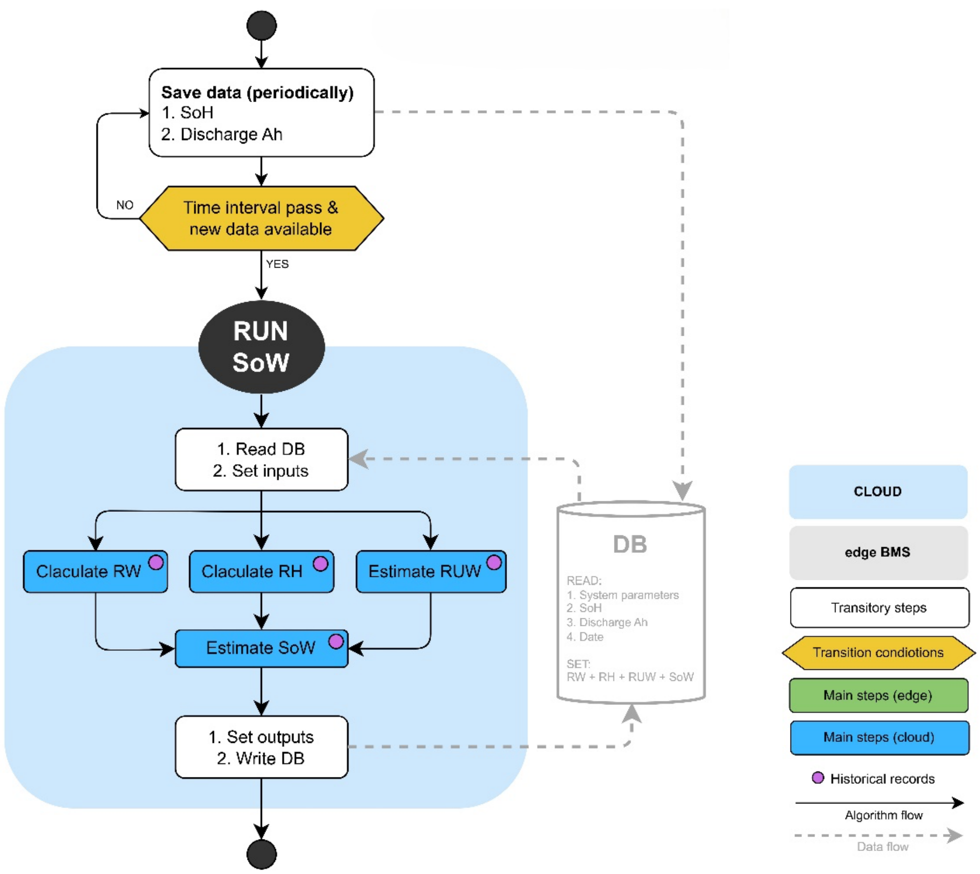

Figure 15 SoW state machine diagram (Pillar 2)

3.3.1.12 Active Balancing

Active balancing will only be performed on demand, which could be a periodic request. For the balancing, voltage and SoC at cell level are required. The algorithm is actually quite simple, as the only update needed is the enabling of the balancer pin. The actual balancing is performed as long as this enabler remains activated. Balancing ends when the balancer is deactivated. This occurs when the balancing time expires, or the cell voltage difference is below a defined threshold (30 mV). In addition, if balancing is requested, but no significant voltage difference between the cells is identified, balancing will finished directly. This is controlled by a minimum difference threshold (100 mV).

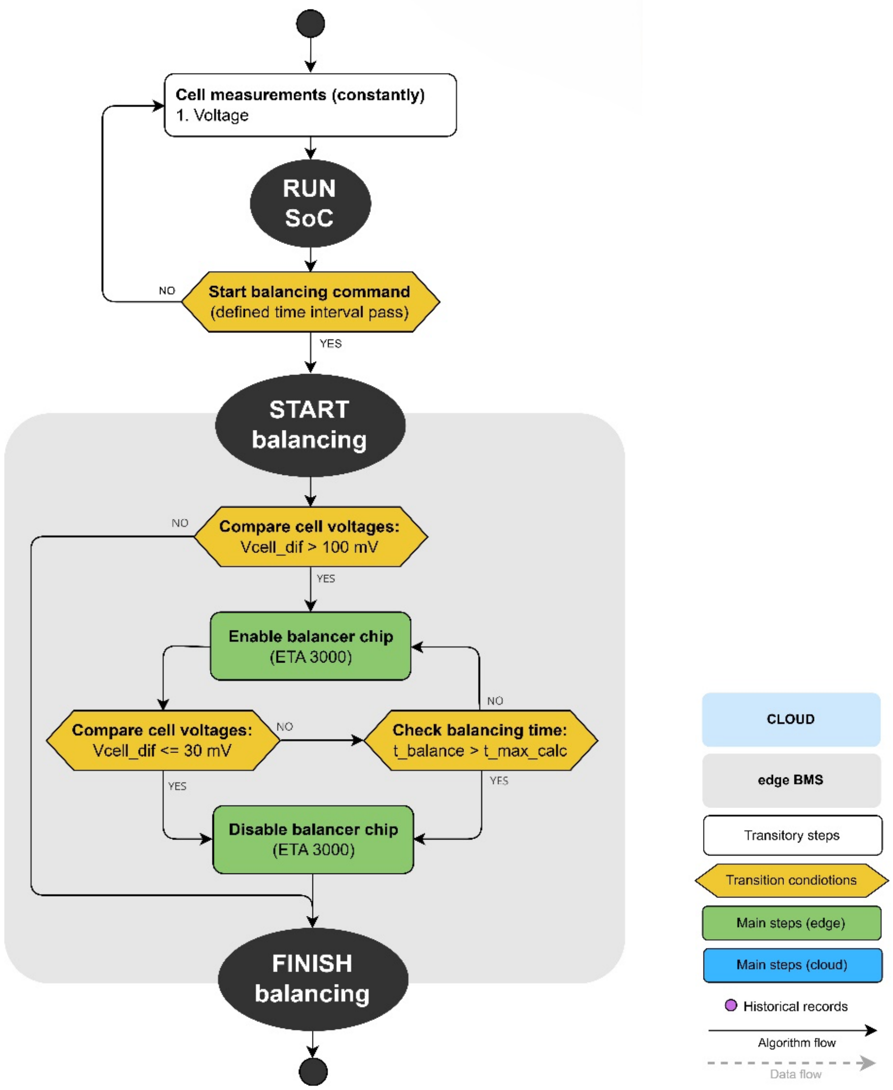

Figure 16 Active balancing state machine diagram (Pillar 2)

4 CONCLUSIONS

This document presents the B2L hybrid architecture and outlines the separation of BMS processes between the cloud and edge systems. It includes state machine diagrams for the SoX estimators and analyses the information flow between cloud and edge BMS processes.

More details as regards the SW/HW BMS specifications and SoX estimators are presented in B2L deliverable D1.3 "*BMS specifications and advanced algorithms for 2nd life*".

5 REFERENCES

[1] https://transportgeography.org/contents/chapter4/transportation-and-environment/greenhouse-gas-emissions-transportation/
[2] https://www.geotab.com/blog/ev-battery-health/
[3] https://blog.chargemap.com/electric-car-battery-replacement/
[4] Monsuru Olalekan Ramoni,Hong-Chao Zhang, "End-of-life (EOL) issues and options for electric vehicle batteries", Elsevier, Clean Technologies and Environmental Policy, vol. 15, pp. 881-891, 2013.
[5] Propulsion Quebec. Lithium-ion Battery Sector: Developing a Promising Sector for Quebec's Economy; KPMG for Propulsion Quebec: Montreal, QC, Canada, 2019.
[6] https://www.sciencedirect.com/science/article/pii/S1110016821001757
[7] Industrial Batteries Market Size, Share & Trends Analysis Report By Battery Type (Lead-acid, Lithium-based), By End Use (Motive Power, Grid-level Energy Storage), By Region, And Segment Forecasts, 2020 - 2027
[8] https://publications.jrc.ec.europa.eu/repository/handle/JRC112543
[9] Yixuan Wang, Baojun Tang, Meng Shen, Yizhou Wu, Shen Qu, Yujie Hu, Ye Feng, "Environmental impact assessment of second life and recycling for LiFePO4 power batteries in China", Journal of Environmental Management, Volume 314, 15 July 2022, https://doi.org/10.1016/j.jenvman.2022.115083
[10] https://eatron.com/battery-management-at-the-edge-vs-in-the-cloud-which-is-best/
[11]https://community.nxp.com/pwmxy87654/attachments/pwmxy87654/tech-days/156/1/EUF-AUT-T3916.pdf
[12]M. Akdere, M. Giegerich, M. Wenger, R. Schwarz, S. Koffel, T. Fühner, S. Waldhör, J. Wachtler V.R.H. Lorentz, M. März, "Hardware and Software Framework for an Open Battery Management System in Safety-Critical Applications", 42nd Annual Conference of the IEEE Industrial Electronics Society, IECON, 2016
[13]https://www.monolithicpower.com/en/battery-management-systems/bms-communication-interface/communication-protocols-in-bms
[14]Shreyas Maitreya; Himani Jain; Priyanka Paliwal, *"Scalable and De-centralized Battery Management System for Parallel Operation of Multiple Battery Packs", Innovations in Energy Management and Renewable Resources, 2021*
[15] Andrea Reindl, Hans, Meier, Michael Niemetz, "Scalable, Decentralised battery management system based on self-organised nodes", 33rd International Conference, Aachen, Germany, 2020.
[16] https://www.mokoenergy.com/centralized-bms-vs-distributed-bms-vs-modular-bms/
[17]https://thebatterypass.eu/assets/images/content-guidance/pdf/2023_Battery_Passport_Content_Guidance_Executive_Summary.pdf
[18] https://thebatterypass.eu/assets/images/technical-guidance/pdf/2024_BatteryPassport_Technical_Guidance.pdf

Co-funded by the European Union

[19]https://www.globalbattery.org/media/pilot/documents/gba-bp-pilot-master.pdf
[20]https://thebatterypass.eu/assets/images/value-assessment/pdf/2024_BatteryPassport_Value_Assessment.pdf

Co-funded by the European Union