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BIG LEAP

Next Generation of Battery Management Systems to increase Interoperability, bridge the Gap between 1st and SL-BESS, Extend Adaptability and emPower battery value chains.

D1.2 - Comprehensive requirements for an Interoperable BMS

A detailed description of parameters that need to be provided and requirements to meet to safely interoperate batteries in flexible scenarios, including a subdivision by BMS layer requirements.

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TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

Executive Summary

This report is deliverable D1.2 written as result of realization of Task 1.2 of Work Package 1. It continues with specification of requirements for the Battery Energy Storage System and focuses on Battery Management System design requirements.

With this idea, the report starts with review of whole system with battery management in mind and derives specification, requirements, and recommendation. It considers hardware and software parts of Battery Management System as well as data management questions. In addition, a review of current state of standards and regulations and their development is prepared, and questions of life cycle and sustainability are reviewed.

Acronyms and abbreviations

AB	Advisory board
AEQ	Active Equalizer
AES	Advanced Encryption Standard
AP	Associated Partner
API	Application Programming Interface
BE	Beneficiary
BESS	Battery Energy Storage System
AFE	Analog Front-End
BIG LEAP	Next Generation of Battery Management Systems to increase Interoperability, bridge the Gap between 1st and SL-BESS, Extend Adaptability and Empower battery value chains.
BJB	Battery Junction Box
BEQ	Bilevel Equalizer
BMS	Battery Management System
BPU	Battery Protection Units
CA	Consortium Agreement
CBC	Cell Balancing Circuitry
CC0	Creative Common Public Domain Dedication
CFS	Certificate on financial statements
COTS	Commercial Off-The-Shelf
DL	Deliverable
DBP	Digital Battery Passport
DC	Direct Current
DCP	Dissemination and Communication Plan
DOI	Digital Object Identifier
DMP	Data Management Plan
DEMO	Demonstrator
EB	Executive Board
EC	European Commission
ECM	Electric Circuit Model
EEA	European Economic Area
EIS	Electrochemical Impedance Spectroscopy
EKF	Extended Kalman Filtering
E-LCA	Environmental Life Cycle Assessment
EMC	Electromagnetic Compatibility

EMS	Energy Management System
EOL	End of Life
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicles
FAIR	Findable, Accessible, Interoperable, and Reusable
FL	First Life Battery
GA	Grant Agreement
GA	General Assembly
GDPR	General Data Protection Regulation
GP	General Public
HPPC	Hybrid Pulse Power Characterization
HV	High Voltage
HVCS	High Voltage Control System
HW	Hardware
IC	Integrated Circuit
ICA	Incremental Capacity Analysis
IEC	International Electrotechnical Commission
IMD	Insulation Measurement Device
IOT	Internet of Things
IP	Intellectual Property
IPR	Intellectual Property Rights
KER	Key Exploitable Results
KoM	Kick Off Meeting
KW	Kilowatts
KPIs	Key Performance Indicators
KWH	Kilowatt - hours
LCA	Life Cycle Analysis
LCSA	Life Cycle Sustainability Assessment
LFP	Lithium Iron Phosphate
LIB	Lithium-Ion Battery
LMO	Lithium Manganese Oxide
LVD	Low Voltage Directive
MFA	Multi-factor Authentication
ML	Machine Learning
MOM	Minute of Meeting
MOP	Maximum Operating Limit
MS	Milestone

MSL	Maximum Safety Limit
NMC	Nickel Manganese Cobalt
NN	Neural Network
OA	Open Access
OCA	Optimal Charging Algorithms
OEM	Original Equipment Manufacturer
ORDP	Open Research Data Pilot Program
ORM	Object-Relational Mapping
OS	Open Science
PD3	Pollution Degree 3
PEQ	Passive Equalizer
PF	Particle Filter
PM	Project Manager
PM	Policy Makers
PO	Project Officer
QA	Quality Assurance
QC	Quality Control
QOS	Quality of Service
R&D	Research and Development
RBAC	Role-Based Access Control
RDBMS	Robust Relational Database Management System
RUL	Remaining Useful Life
RH	Relative Humidity
RMP	Risk Management Plan
ROL	Result Ownership List
RSL	Recommended Safety Limit
RUL	Remaining Useful Life
RUL1L	Remaining useful life in first life application
RUL2L	Remaining useful life in second life application
SC	Scientific Community
SC	Switched Capacitor
SEU	Single Event Upset
SIL	Safety Integrity Level
SLB	Second Life Battery
S-LCA	Social Life Cycle Assessment
SOC	State of Charge
SOE	State of Energy
SOH	State of Health
SOP	State of Power
SOS	State of Safety
SOX	State of X
SW	Software
TLS	Transport Layer Security
TMS	Temperature management system
TOTP	Time-based One Time Password
TRL	Technology Readiness Level
UL	User Interface
WD	Working Day
WP	Work Package
WPLB	Work Package Leader Board

Introduction

Battery management system (BMS) is the control and intelligence of the battery system and has an influence on many aspects of whole system: structure, operation, diagnostics and maintenance, functionality, and safety. Therefore, in the phase of specification of requirements to the BMS unit, interoperability, requirements of individual components and the whole system operation should be considered.

For this reason, the report includes review of functionality and interfaces in the battery system, review of relevant standards and internal guidelines of consortium companies, suggestions to next steps in standards and processes improvement, considerations about life cycle and sustainability which defines hardware and software requirements and recommendations to hardware, software, and data structure of BMS.

The structure of the report consists of 4 parts. The first part is devoted to review of the battery system and its use cases, the second considers requirements to hardware of the BMS. The third part assesses software functionalities and targets, last one reviews BMS impact and formulates recommendations based on sustainability, standards guidelines, and life cycle considerations.

1. BIG LEAP system overview from BMS aspects point of view

The Big Leap system must interact with various devices to fulfil its functionalities and must be highly flexible to achieve the required interoperability. The hardware requirements are defined to meet the key performance indicators (KPIs) and ensure the seamless integration of the Big Leap system into the demonstration facilities described in Deliverable 1.1.

The hardware requirements are defined using a top-down approach. First, an illustrative context diagram for each Big Leap system demonstrator is presented. The context diagrams show the components involved in each demonstration use case. Next, a use case diagram identifies the actors interacting with the Big Leap system and the types of interactions that will occur. Finally, the interactions between the actors and the Big Leap system functions are described in detail.

1.1. Big Leap's Context Diagrams

The context diagrams represent the overall system architectures for a Battery Energy Storage System (ESS) that are applicable to each of the Big Leap's demonstrators at EDF and Eaton, and the virtual demonstrator at Masen. They also emphasize what are the control units developed under the Big Leap's project, what are Commercial Off-The-Shelf (COTS) components, and what components are specific for each Use Case.

The core components include cells forming first-life modules, which are managed by a combination of proprietary and Big Leap's slave BMSs. These modules are part of a battery rack equipped with a thermal management system that regulates the temperature of the modules. Each ESS string includes one or more battery racks, which can be connected to a DC/DC power converter that regulates the ESS string's output voltage and power. Additionally, each ESS string is equipped with a Battery Protection Unit (BPU) that supervises battery power, manages connection and disconnection, and interrupts overcurrent events, and a Master BMS, which supervises and governs the rack components. Alternatively, if all the modules from the different racks are equal, then the ESS Strings can be coordinated so that they are connected in parallel. Consequently, ESS Strings are aggregated in the so-called ESS. The ESS is equipped with power supplies to source energy to the control units, thermal management system and, in general, all the electric/electronic/programmable electronic devices of the ESS. Provided that there are diverse Master BMSs in the ESS with unique communication protocols, the Edge device offers a common standardized interface to each Master BMS, and connectivity to the Cloud. The Edge device performs the necessary control to coordinate Master BMS and the DC/DC converters in the system according to the Energy Management System (EMS) requests.

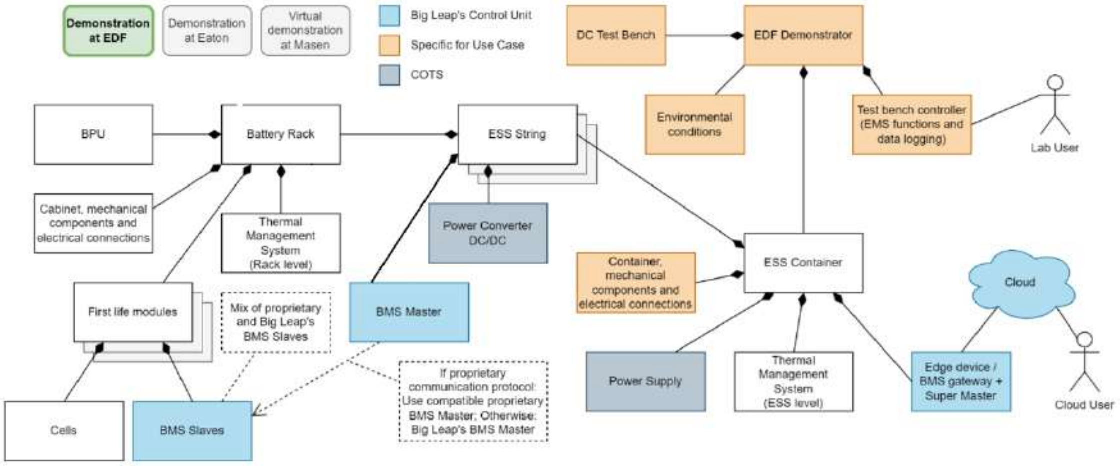

Figure 1. Context diagram of the Use Case 1: Demonstration at EDF.

Figure 1 illustrates the context diagram of the Big Leap project demonstration at EDF. The ESS of the EDF demonstrator requires three types of ESS String, according to the first life modules included in the battery racks: ORCA ENERY from Corvus Energy, NOVA from Solitek, Standard Range Battery Pack from Siro Energy.

The DEMO at EDF will include a DC Test Bench to charge and discharge the ESS. This DC Test Bench includes a Test bench controller with some control capabilities to communicate and manage the ESS, as well as data logging. The ESS solution will be containerized, together with the required thermal management system at ESS container level, and the necessary mechanical and electrical components.

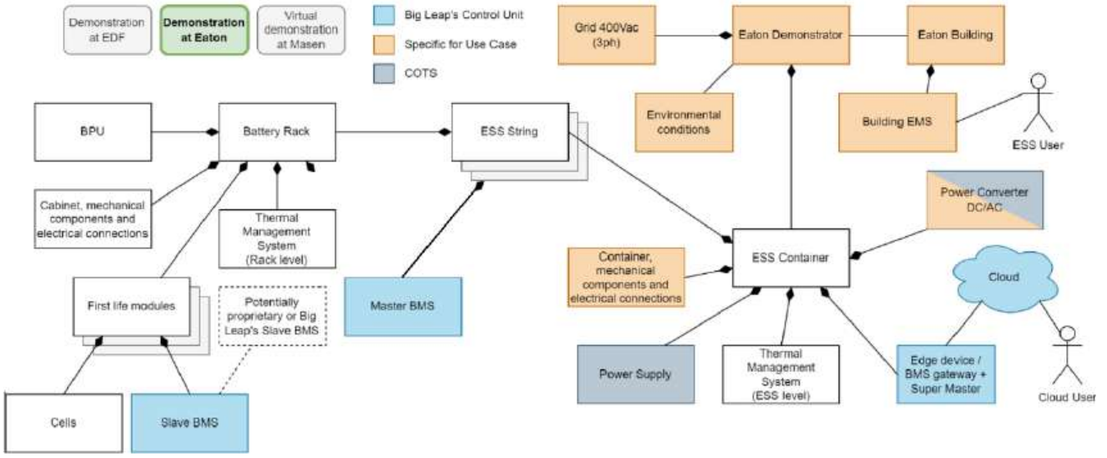

Figure 2. Context diagram of the Use Case 2: Demonstration at Eaton.

Figure 2 depicts the main components of the Eaton demonstrator. There are two key components relevant to this demonstrator, in comparison with Use Case 1: a physical EMS to coordinate the ESS Strings, and a DC/AC power converter to interface the ESS with the grid.

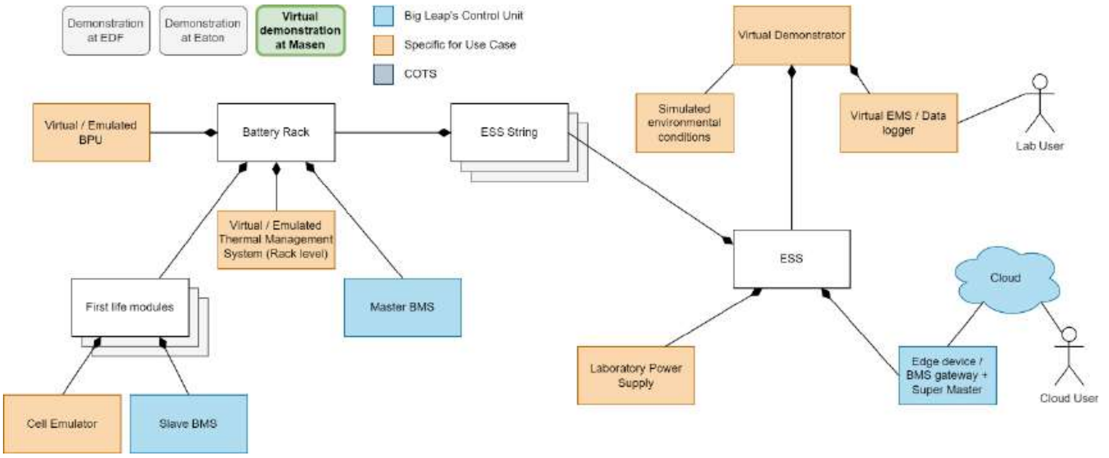

Figure 3. Context diagram of the Use Case 3: Demonstration at Masen.

Figure 3 shows the third Use Case inside the Big Leap project: the virtual demonstrator at Masen facilities. In this case, the integration of the ESS is minimal, and its main purpose is to verify and validate the control units and the runnable algorithms in a controlled environment. The first life modules, instead of real cells, include emulated cells to provide the required information to the BMS Slaves.

1.2. Big Leap's systems use case diagram

The use case diagrams show the interactions between the Big Leap's control units and the different actors and components shown in the context diagrams. The Big Leap's control units are Slave BMS, Master BMS and Edge device. In addition, the Big Leap's control units need to comply with environmental requirements, as well as the project objectives and relevant standards. These requirements are described in Section 2.1.

1.2.1. Slave BMS use case

The Slave BMS plays a pivotal role by providing real-time measurements to the Master BMS, which then configures and controls the Slave BMS. The interactions of the Slave BMS are shown in Figure 4.

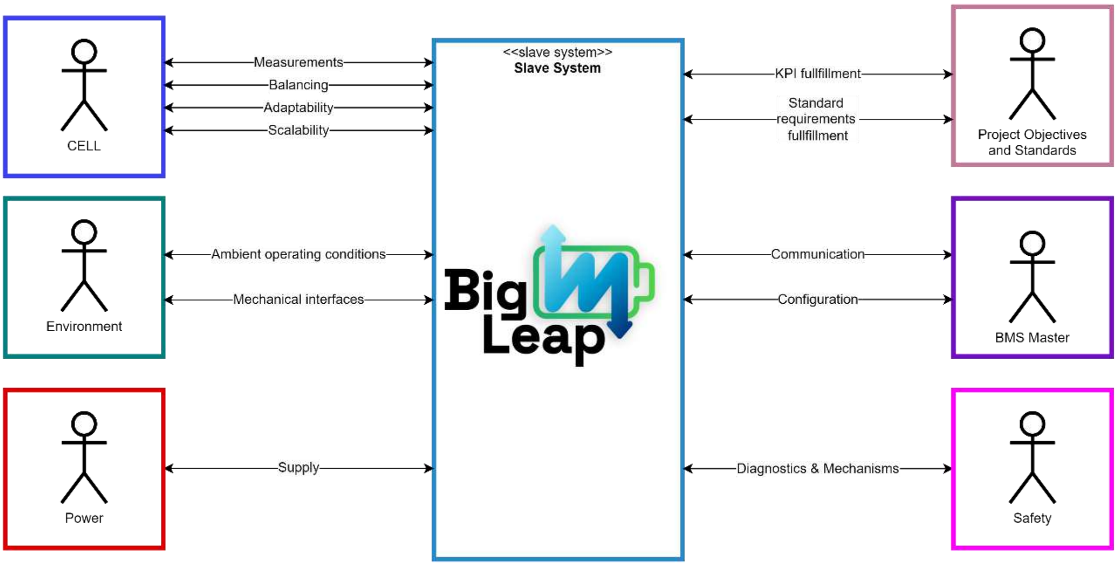

Figure 4. Use Case Diagram of Slave BMS

The Slave BMS needs to interface with the cells of all first-life modules, ensuring accurate monitoring. The Slave BMS shall be equipped with sensors and measurement circuits that monitor the voltage of all the battery cells on a module, and the temperature of each cell or group of cells. It must be capable of interfacing with NMC (Nickel-Manganese-Cobalt), LFP (Lithium Iron phosphate) and LMO (Lithium Manganese Oxide) cell chemistries, where in Table 1 shows the minimum, nominal and maximum voltage levels for each chemistry. The BMS needs to measure up to 16 cells connected in series and up to 8 temperature sensors.

Table 1 Voltage range vs cell chemistry

Cell chemistries	Nominal voltage	Minimum voltage	Maximum voltage
NMC Corvus	3.68 V	3 V	4.2 V
NMC Siro	3.65 V	2.2 V	4.2 V
LFP Solitek	3.2 V	2.65 V	3.65 V
LMO Eaton	3.75 V	3.1 V	4.1 V

Additionally, the Slave BMS needs to ensure that all cells within the battery pack maintain a uniform charge level. This process, known as cell balancing, is critical for maximizing the efficiency and lifespan of the battery module and will be done with passive balancing.

The measurements done by the Slave BMS are provided to the Master BMS in real-time. Furthermore, the Master BMS also configures the Slave BMS. The most common communication protocols between Slave modules and the Master BMS are TPL or isoSPI, though CAN or Modbus may also be used in certain cases. In this scenario, the requirement for the Slave BMS would be to utilize a daisy-chainable communication protocol.

The Slave BMS is self-supplied directly through the battery module and operated over a wide range of voltages from 10 V to 90 V.

The Slave BMS shall have some type of diagnosis to detect any operating anomaly, such as an open wire on the voltage or temperature path.

1.2.2. Master BMS use case

In BMSs, the coordination between various components is crucial for ensuring optimal performance and safety. At the heart of this coordination lies the Master Battery Management System (Master BMS), which plays a pivotal role in overseeing and managing the operation of multiple Slave BMS units within a battery string. This hierarchical structure allows for efficient monitoring and control across the entire battery system. Figure 5 illustrates the interactions of the Master BMS.

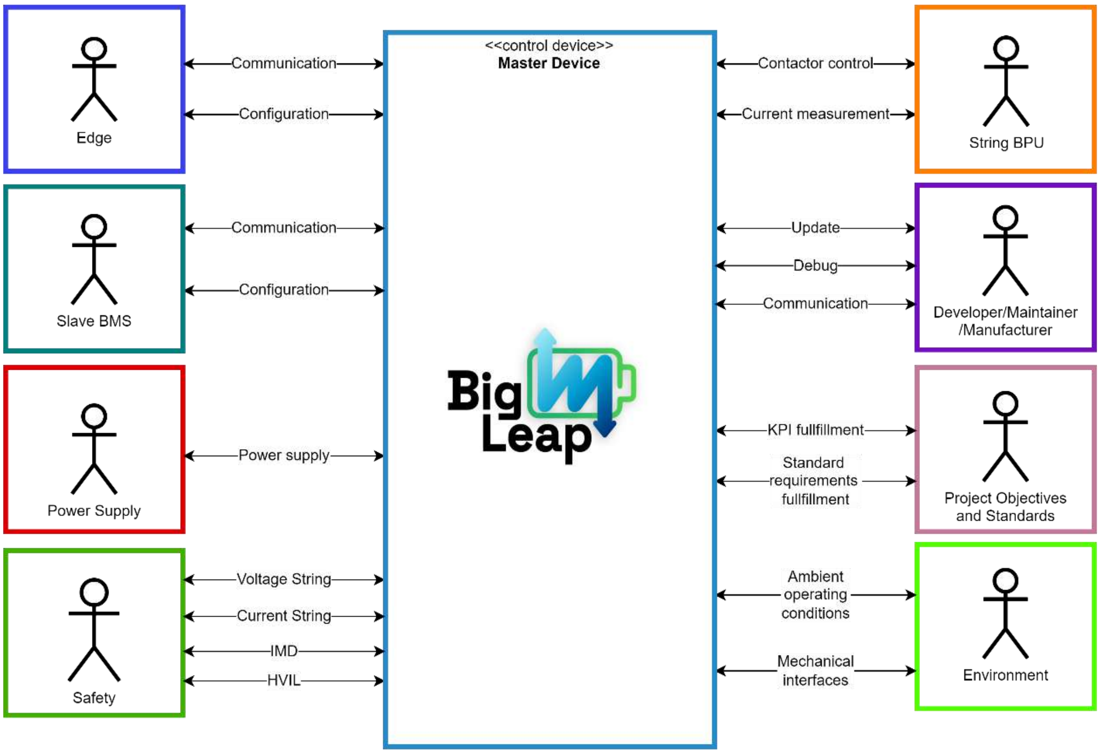

Figure 5. Use Case Diagram of Master BMS

The Master BMS interacts with Slave BMS units by collecting and aggregating data from each Slave unit on the string. Also, the Master BMS sends control commands to the Slave units to perform actions such as cell balancing and voltage and temperature measurements.

Additionally, the Master BMS needs a bi-directional communication with the Edge device to send and receive required data, reconfigure the BMS settings, and receive operational status updates. The communication between the Master BMS and the Edge device can be Modbus TCP or CAN bus communication.

Furthermore, the Master BMS communicates with and controls the BPU, which includes two main contactors (one per pole) to perform charge/discharge activation sequences and a precharge circuit. Also, the Master BMS must be able to monitor whether each contactor has successfully opened or closed through an acknowledgement mechanism.

To guarantee safe operation and monitoring, the Master BMS shall acquire several parameters from the system. The Master BMS measures the current flow through the battery strings via the current sensor installed on the BPU. In addition, the Master BMS monitors the string and the module voltage as well as the ambient temperature. This helps to ensure operation within safety limits.

Furthermore, the Master BMS must measure insulation using an IMD device to protect personnel from electrical hazards and shall also feature of heartbeat signal for safety reasons, as monitoring of the communication integration.

The Master BMS needs communication to allow the developer to easily debug, verify and validate the Master BMS during the design and upgrade processes. In addition, it is necessary to implement this or other communications to perform maintenance tasks such as software version verification.

The Master BMS receives its power from an external power supply connected directly to the battery or from the Edge device. This power must be within a voltage range of 12V to 24V. On the other hand, it can provide external power supply to supply external elements or systems such as external sensors, elements of the string BPU or Slave BMSs that require external power supply.

1.2.3. Edge Device use case

In sophisticated battery management systems, the edge device plays a critical role in bridging the communication between different system components. Specifically, Figure 6 illustrates the interactions of the edge device, which serves as an essential abstraction layer between the Master BMS units and the Energy Management System of the container. This intermediary functionality is crucial for ensuring smooth and efficient data flow, facilitating seamless integration and management of the overall battery system. By decoupling the Master BMS from the EMS, the edge device enhances the system's flexibility and operational efficiency.

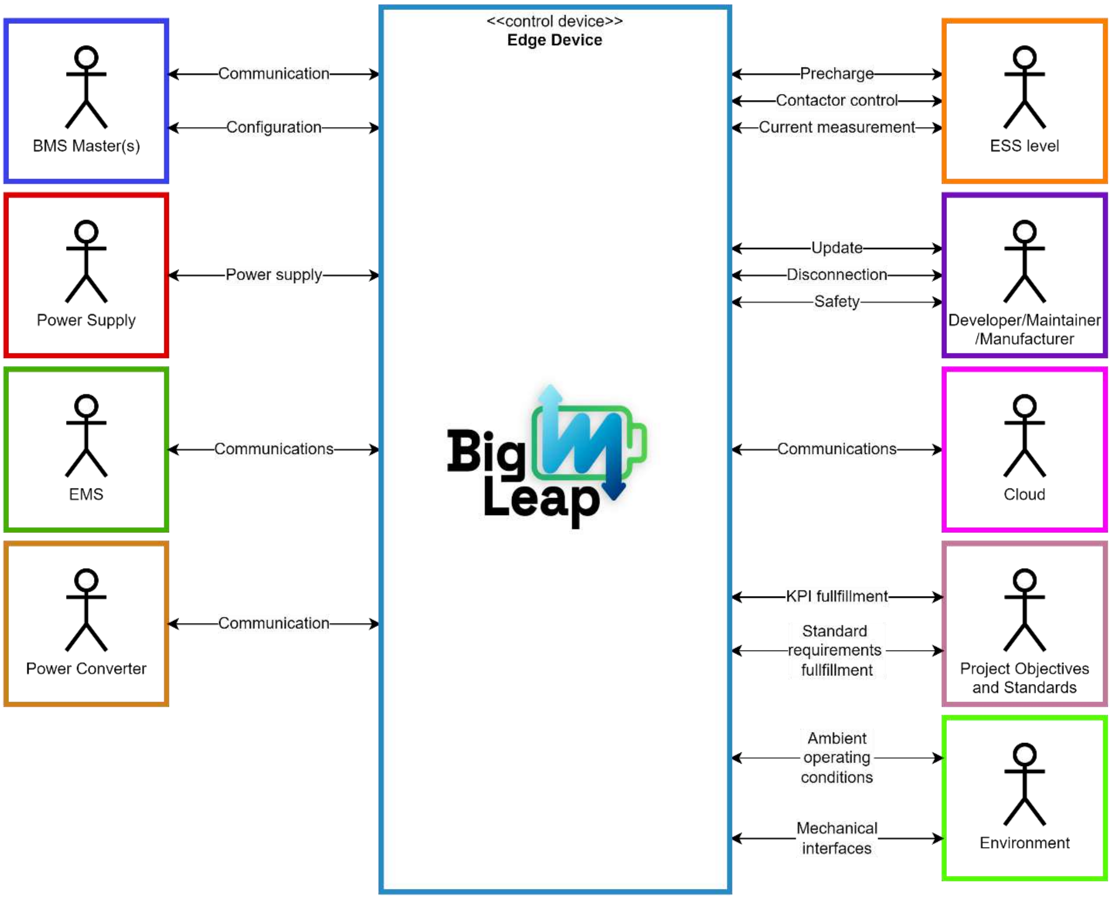

Figure 6. Use Case Diagram of edge device.

As mentioned in the section of the Master BMS, there is bi-directional communication between the Master BMS and the Edge device, to send and receive the necessary data, reconfigure Master BMS settings and receive operational status updates. This communication protocol can be Modbus TCP or CAN bus communication, so the Edge must support both.

Additionally, the Edge device needs to establish bi-directional communication with the EMS or system controller using either Modbus TCP or CAN bus. Therefore, the Edge device must include support for both Modbus TCP and CAN bus to ensure compatibility with the systems analysed.

Furthermore, the Edge device needs to include some type of communication with the cloud to send and receive data for performing remote and predictive maintenance, self-diagnosis and fault detection, specific safety metrics and other actions explained in section 3.2.

As also has mention in the section of Master BMS, it is necessary communication that allow the developer to easily debug, verify and validate the Edge device during the design and upgrade processes. In addition, it is necessary to implement this or other communications to perform maintenance tasks.

The Edge device also is powered by an external power supply, operating within a voltage range of 12V to 24V. On the other hand, the Edge device can provide external power supply to supply external sensors or systems, such as the Master BMS or elements of the TMS.

The DC/AC converter is controlled by the EMS or system controller. However, if a DC/DC power converter is installed on the ESS, it will be controlled by the Edge device. For this reason, the Edge device needs bidirectional communication to control the power converter of all the strings. Figure 7 shows the system communication architecture with DC/DC converters.

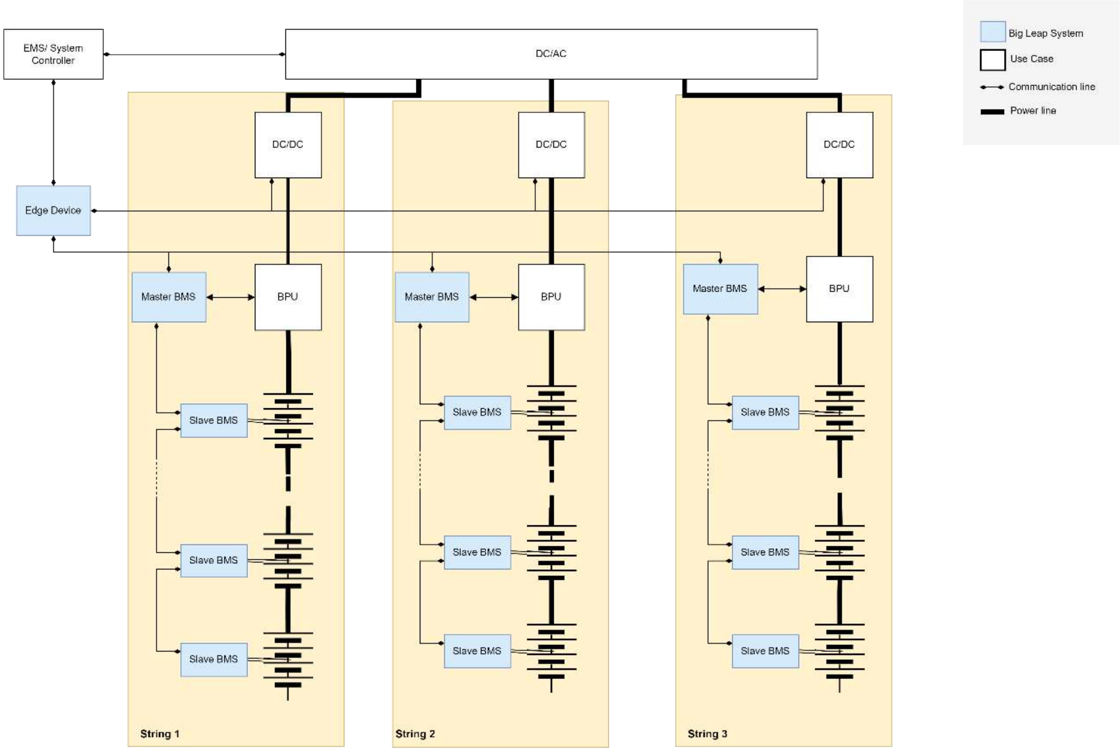

Figure 7. Architecture of the communications between Big Leap's control systems, power converters and external systems.

In addition to the string BPU described in section 1.2.2, some ESS systems may include protective elements, such as contactors or relays, in a higher layer. This protection system is called the ESS BPU and is controlled by the Edge device.

1.3. Cell performance

Understanding the performance of individual cell within a battery is crucial for optimizing energy storage solutions across various applications. A cell is a fundamental building block in battery technology, where its performance directly impacts the overall efficiency, reliability, and lifespan of the battery system. Key Performance Indicators (KPIs) are metrics which assess overall performance, efficiency, and reliability. KPIs for a cell are capacity, energy density, power density, cycle life, internal resistance, self-discharge rate, safety, temperature/operating range, cost, and environmental impact. Second-life batteries (SLBs) necessitate very thorough testing and readjustments to ensure safe and reliable operation

As per the European Commission, "The existing EU Batteries Directive, dating back to 2006, is no longer up-to-date". The European Union has established a comprehensive regulatory framework for batteries, including second-life batteries. The Regulation (EU) 2023/1542 [1] addresses the entire life cycle of batteries, covering aspects such as sustainability, performance, safety, collection, recycling, and information for end-users and economic operators. Before employing a battery for second life purposes, a suitability test must be conducted to ensure that the battery is usable.

1.4. Cell Performance Testing

1.4.1. Internal Resistance Testing / Tracking

Internal resistance is an indicator of the battery's overall health and condition. When a battery ages or undergoes stress, its internal resistance tends to increase due to changes in electrode materials, electrolyte degradation, or physical damage. Higher internal resistance contributes to increased heat generation during operation. This factor is particularly significant in SLBs, where managing thermal conditions becomes more challenging due to increased risk of internal faults or irregularities. BMS algorithm should rely on real-time measurements of internal resistance to dynamically adjust operational parameters. Early detection of resistance variations helps in diagnosing cell health issues, optimizing charge-discharge cycles, and preventing premature failure. Paper in [3] proposes three estimating methods that require a small set of data to get the estimation internal resistance of SLB.

1.4.2. Capacity Testing

Constant Current Discharge and Pulse Load tests are simple and easy to do making them suitable for initial capacity assessment. Hybrid Pulse Power Characterization (HPPC) and Electrochemical Impedance Spectroscopy (EIS) offer deeper insights into battery dynamics and internal resistance, making them suitable for detailed characterization. But these tests require specialized equipment. State of Charge (SoC) coupled method is simple and non-invasive method which estimates the capacity based on the relationship between voltage and SoC during discharge.

1.4.3. Rate Capability Testing

Rate Capability Testing involves subjecting the battery cell to various charge and discharge rates, typically ranging from very low to very high currents. It provides insights into how the cell performs under varying load conditions encountered in real-world applications. It determines the maximum current at which the cell can discharge without a significant drop in voltage. It also evaluates the suitability for fast-charging applications as there is a possibility for excessive heat generation. It assesses the cell's temperature rise during rapid charge and discharge cycles, helping to optimize thermal management systems.

1.5. Cell Performance Monitoring

1.5.1. State of Charge (SoC) Monitoring

SLBs exhibit different behavior as compared to new batteries. The charging/discharging curves vary between the SLB and new batteries. Cells within SLB can differ in terms of internal resistances, capacity, and other KPIs making it complex for the BMS to accurately predict SoC. The BMS algorithm must account for these differences to accurately determine the SoC. It is crucial for utilizing the battery capacity without overcharging or undercharging, both of which can accelerate degradation, to reduce premature aging and to reduce potential safety hazards. Therefore, Artificial Intelligence and Machine Learning driven techniques present a viable solution to improve the adaptability of BMS. ML can utilize the past data to learn and make decisions based on insights providing a dynamic system capable of accurately monitoring and managing the crucial parameters [4]. Among the algorithms currently utilized or in development, there are the Extended Kalman Filter (EKF), Particle Filter (PF), and Random Forest model.

1.5.2. State of Health (SoH) Assessment

State of Health (SoH) assessment refers to evaluating the current condition or health status of a battery. It is crucial for determining the remaining capacity, performance capability, and overall reliability of the battery. SoH in SLB is influenced by factors such as cycling history, aging, temperature exposure, and operational conditions. Continuous monitoring by BMS tracks degradation trends, enabling timely adjustments in charging profiles and operational parameters to maintain optimal battery performance. SoH can be assessed in two ways: intrusive methods and non-intrusive methods. Intrusive methods require the physically accessing the battery and non-intrusive methods can be performed without physically altering or accessing the battery. The BIG LEAP BMS should focus more on non-intrusive methods. Incremental Capacity Analysis (ICA), Electrochemical Impedance Spectroscopy (EIS) are generally considered non-intrusive techniques [5]. EIS involves measuring the impedance response of a battery or electrochemical cell by applying small amplitude AC signals and analysing the resulting impedance spectrum. The information obtained through EIS can be analysed using a neural network (NN) to estimate the State of Health (SoH). New methods have also been proposed to reduce the time taken to perform EIS measurements without a significant loss of data [6]. Studies suggest that these methods, while highly accurate can be challenging to implement online due to variations in operating conditions between the laboratory and real-world environment, often leading to interruption in normal operations. One study suggests using adaptive method like Kalman Filter (can be done while under operation) to manage internal state variables iteratively and employ loop-up tables containing ageing data [7]. This method comes with a drawback of being computational resource intensive.

1.5.3. Cell Balancing and Equalization

Voltage imbalances among battery cells can decrease storage capacities and, at worst, lead to explosions or fires, posing significant obstacles to the safe and efficient operation of battery-powered appliances. BMS to set upper and lower voltage thresholds for individual cells and the overall battery pack to prevent overcharging, over discharging, and cell imbalance. BMS balances cell voltages through passive (resistive balancing), active (switching current between cells), or hybrid methods to equalize charge levels and maximize capacity utilization. Switched Capacitor (SC) equalizers which are passive equalizers (Double-tiered, modularized, resonant SC based equalizers, and chain-structured) are viable options because of their low cost, simple control strategy, small size and simple implementation [8]. To overcome the reduction in equalization speed in conventional SC equalizers with increase in number of cells, different topologies like double-tiered, modularized chain-structured have been developed. To reduce hard-switching losses resonant SC based cell equalizer has been developed. To ensure soft switching inductors are connected in series with each capacitor.

BEQ is a PEQ/AEQ hybrid that operates at two different voltage levels. This can also be looked into for cell equalization [9].

1.5.4. Temperature Monitoring for Each Cell

Temperature sensors integrated into BMS monitor and regulate cell temperatures within safe operating limits to prevent thermal runaway and degradation. Maintaining optimal temperatures enhances safety, performance, and longevity of SLBs, especially under varying operational conditions. Continuously collecting temperature data to track changes like degradation pattern during various operational conditions. This real-time monitoring allows for early detection of abnormalities that could lead to degradation or safety risks. Incorporating temperature data into BMS algorithms for dynamic thermal management. This includes adjusting charging rates, current limits, or cooling strategies based on real-time temperature readings to optimize battery performance and lifespan. One study suggests that sensors should be implemented inside the battery cells to accurately measure internal temperatures. This is crucial because internal temperatures can significantly differ from surface temperatures, especially during high-rate charging or discharging [10]. Using temperature data to calculate safety margins during operation, especially under stress conditions such as fast charging or high current discharging. This ensures that operational limits are not exceeded, reducing the risk of thermal runaway.

1.5.5. Current Limit and Overload Protection

BMS should regulate current flow during charging and discharging processes to prevent overcurrent situations that can lead to overheating and capacity loss. Controlled current management reduces stress on cells, mitigates thermal risks, and maintains consistent performance over the battery's operational life. High current levels accelerate aging processes like electrode degradation and electrolyte decomposition, reducing battery capacity and cycle life. BMS should limit currents based on real-time conditions. BMS to implement safeguards such as current limiters and emergency shutdown protocols to prevent catastrophic failures caused by excessive currents.

1.5.6. Communication, Data Logging and Fault Diagnostics

BMS continuously logs operational data such as SoC, SoH, temperatures, currents, and voltage levels to monitor trends, analyse performance, and optimize operational strategies. There should be utilisation of standard communication protocols like CAN bus, Modbus to enable remote monitoring, diagnostics. BMS should identify and diagnose issues such as cell degradation, module faults, or BMS malfunctions through comprehensive fault detection algorithms and diagnostic routines. It should employ tools such as fault codes, alarms, and predictive analytics to pinpoint the root cause of issues, streamline troubleshooting, and expedite corrective actions.

2. BMS hardware assessment

2.1. Specific hardware requirements

2.1.1. Environmental requirements

The ESS inside the container must operate reliably under the following operating conditions:

- Relative humidity <99%.
- Temperature of operation outside the container from -20 ºC to 50 ºC.
- Temperature of operation inside the container from 0 ºC to 35 ºC.
- Altitude up to 2.000 m.
- Pollution degree according to IEC 60664-1 of PD3.

The control systems shall operate reliably in the operating conditions of the ESS, with the following exceptions:

- It is assumed that batteries, control systems and nearby equipment will generate local micro-environments. Then, the applicable temperature of operation is from 0 to 55 ºC.
- It is assumed that the container provides at least one degree of protection against pollution. Then, the applicable pollution degree according to IEC 60664-1 is PD3.

The Big Leap's control systems need to be physically mounted within the battery modules, rack, or ESS. To this end, the first life BMSs already include some mechanical fixations, such as screw holes. However, it is required that the battery rack provides a configurable interface to allocate the different first life Master BMSs, as well as adequate cooling, and allowing easy access for the connectors.

2.1.2. Insulation requirements

The ESS and Big Leap's control systems shall provide protection against electric shock, according to applicable standards (see Section 4.2). Figure 8 illustrates the overall assumed scenario in which the ESS and the control systems shall operate safely.

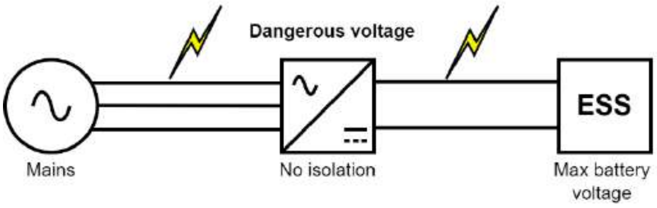

Figure 8. Input conditions and scenario for protection against electric shock and insulation coordination

The battery system shall be protected against dangerous voltages, as well as temporary overvoltages that can take place inside the ESS or in the grid. The following conditions are assumed:

- Maximum battery voltage: 1.000 Vdc
- Mains:
    - Voltage: 230 / 400 Vac
    - Overvoltage category III
    - TN network
- Pollution degree: PD3

2.1.3. Project objectives and standards

The system design must comply with the requirements described in standards specific to the project. The relevant standards are described in Sections 4.2 and 4.2.

The following project KPIs are relevant to BMS hardware:

- **O103**: Battery system operation and battery reconfiguration at module level. The Big Leap system shall be mechanically compatible with at least four different types of modules.
- **O107**: Increase BMS electronic lifetime. The BMS design shall be optimised to reduce stress factors to extend useful lifetime. The BMS components shall be selected to withstand operational conditions that are outside the expected top operational requirements. Therefore, components shall be selected to withstand 125 ºC of operational temperature or higher. In addition, the Big Leap's Master BMS's design shall allow to reuse available slave BMS components.
- **O302**: Increase the Energy efficiency of the BMS system. Energy efficient components shall be prioritised during BMS design, such as high efficiency power supplies.
- **O303**: BMS adaptability to different sizes and configuration. The Big Leap system hardware shall be able to adapt from 1P1S module configuration, up to 25P25S module configuration (25 parallel strings, each integrating 25 series modules). In addition, the number of cells and temperature sensors in each module shall also be configurable.
- **O306**: Open source BMS. All the resulting documentation of hardware shall be made available.

2.2. Analysis of BMS-Master and BMS-Slave components

This section introduces the first life BMS and highlights potential constraints and solutions for their integration.

Five first life BMS have been identified from the first life modules:

1. Orca Energy - Corvus Energy
2. Blue Whale - Corvus Energy
3. Dolphin Energy NextGen - Corvus Energy
4. NOVA - Solitek
5. Standard Range Battery Pack - Siro Energy

On the other hand, the first life module "xStorage second life (XSTH1U12EV2)" from Nissan (Eaton) does not include any BMS to monitor the cells, and in case it is used, it will require an independent BMS.

Alternatively, the foxBMS 2 platform will be used as a baseline for Big Leap's developments, to cover the functional gaps required to operate the first life BMS, or as a substitution for first life BMSs that do not cover the technical requirements.

The BMS can enable the battery scalability in two dimensions: capacity and voltage.

Regarding the capacity scalability, two common approaches are taken: 1. the cells are paralleled inside the module to form a matrix of serial and parallel cells, 2. modules or racks, together with some electric protections, are paralleled. Parallelizing cells is a lot simpler and cheaper, but parallelizing modules or racks allow to quickly replace faulty batteries. Also, parallelizing modules or racks require that the BMS controls the electric protections, as well as manage the connection of the parallel strings. In stationary applications, usually both approaches are applied together to build high energy modules, while also allowing to parallel high voltage racks.

Batteries can scale up in voltage by serialising cells. This implies that the BMS shall be able to monitor all the cells in series and must have the means to chain monitoring devices. In addition, scaling up the voltage presents electrical risk, and thus, the BMS must include isolation between dangerous voltages and accessible parts of the electronics. Regarding the voltage scalability, most of the first life BMS can be serialised to achieve a high voltage battery pack. All Corvus Energy BMSs can operate above 1.000 V, while Solitek BMS is limited to 1.000 V, and Siro Energy BMSs can work up to 650 V.

Regarding how the BMS is powered, usually, the cell monitoring (Slave BMS) is powered directly from the cells. The Slave BMSs from Corvus Energy and from Siro Energy are directly powered from the module cells. Conversely, the module controller from Solitek is powered externally with an input voltage range of 8-72 V.

The most typical Battery Management System communication protocols of first life BMS are illustrated in Figure 9. Siro Energy BMSs use TPL or isoSPI for this communication, depending on the cell monitoring IC. Solitek BMS requires CANbus communication between Master and Slave BMS. In contrast, the other first life BMS systems do not disclose their communication methods, requiring the Master BMS of the first life to interact with the proprietary Slave modules. Furthermore, Solitek, Eaton, and Siro Energy use CANbus communication between Master BMS and EMS, whereas Corvus Energy employs Modbus TCP communication.

Additionally, the BMS Master may communicate with the Battery Junction Box (BJB) or the High Voltage Control System (HVCS). For Siro Energy, CANbus communication is also used. The BMS Master also has specific communication channels for user or maintenance purposes, such as development, reconfiguration, or updates. Siro Energy uses CAN bus communication for these purposes as well.

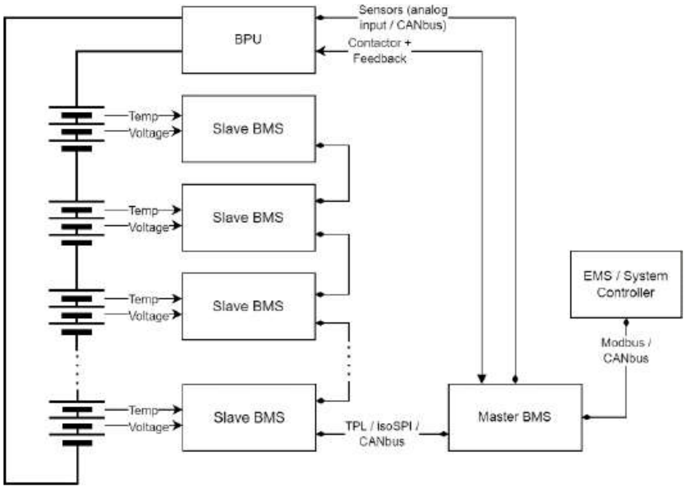

Figure 9. First life BMS most common communication protocols

For enhanced safety, BMSs include extra sensors and features such as emergency stop circuits (interlocks) and ground fault detection to prevent electrical hazards. Additionally, they can include other sensors, such as in the case of Siro's module, which incorporates crash, pressure, gas, and humidity sensors to detect and respond to mechanical impacts, pressure changes, hazardous gas emissions, and humidity levels, ensuring comprehensive monitoring and protection under various operating conditions. The mechanical integration of the modules as well as the physical dimensions of the modules are shown in **Error! Reference source not found.**.

Table 2 FL module mechanical characteristic

Module	**Integration**	**Dimensions (D x W x H) mm**
ORCA ENERGY	Rack	420 x 164 x 600
Blue Whale	Rackless	1165 x 904 x 241
Dolphin Energy NextGen	Rackless	660 x 488 x 100
NOVA	Rackless	511.1 x 200.4 x 228.1
Standard Range Battery Pack	Rack	356 x 420 x 110.5

2.3. Functional requirements for the hardware components derived from foxBMS 2 applications

The following lists the requirements regarding the hardware components itself (based on the required functionalities) and furthermore the derived requirements.

The BMS-Master and the accompanying BMS-Slave must consist of components that enable the following features:

- The BMS must measure the individual cell voltages with at least 30 Hz and ±2 mV accuracy.
- The BMS must enable cell balancing (active or passive).
- The BMS must measure the temperature with at least 1 Hz and ±0.5 °C accuracy.
- The BMS must measure the current with at least 30 Hz and ±0.1 A accuracy.
- The communication between the BMS-Master and the BMS-Slave must be differential.
- The BMS must communicate via a CAN bus to the higher-level control unit.
- The BMS must measure the insulation and communicate the data to the higher-level control unit.

3. BMS software assessment

3.1. Low-level software requirement

This sub-section details the low-level software requirements for the BIG LEAP multi-operational Battery Management System (BMS) firmware. This section will outline the detailed requirements necessary for the system and provide a comprehensive means to express the needs of the BIG LEAP multi-operational BMS.

The BIG LEAP project uses the foxBMS 2, developed by Fraunhofer, as a baseline for developing the multi-operational BMS. Consequently, the software framework for a custom foxBMS 2[1] low-level module (embedded model) also applies here. As per the BIG LEAP project grant agreement, both VTT and Fraunhofer are involved in another project, BATMAX, which also considers the foxBMS 2 as a starting point for further development; the outcome will be applied to BIG LEAP. Thus, the hardware and software requirements from the BATMAX project are mostly applicable to this project. The low-level software requirements for the multi-operational BMS cover a wide range of sections, including measurement functionalities, communication interfaces, optimization and control, battery protection, battery state estimation and performance, and error mitigation and handling. Each of these sections is crucial for the effective operation of the BMS.

3.1.1. Measurement functionalities

Voltage measurement - It is a critical function that must be implemented to ensure the safety of the battery system. It is imperative to never exceed the specified upper and lower voltage limits in lithium-ion battery cells. The voltage measurement

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[1] https://docs.foxbms.org

function monitors and ensures that the battery cell voltages stay within these limits throughout the battery system's lifetime, as specified in the cell datasheet. Any violation of these limits can lead to hazardous situations, making the voltage measurement function a key safety feature.

The BMS must periodically measure ESS voltage at the cell, module, pack, and string levels with the specified sampling rate defined in section 3.3.

Current measurement - *The* current per battery cell/cell block is a key safety factor for the battery system. This measurement is important in calculating the battery current per string and per cell. Additionally, the battery current per pack is also an important measure to consider.

The BMS must measure the string and pack current at regular intervals using the specified sampling frequency defined in section 3.3.

Temperature measurement - Lithium-ion batteries have strict temperature limits (maximum and minimum) that must be maintained for safety. A temperature measurement function is needed to detect if the temperature goes outside the safe operating range defined in the cell datasheet. If the temperature exceeds these limits, it can lead to hazardous events.

The BMS must measure all the LIB cell temperatures at regular intervals with the specified sampling frequency defined in section 3.3.

3.1.2. Communication interfaces

CAN communication interface and baud rate - CAN is a widely used, straightforward, and standardized communication protocol for various applications. It is not necessary to limit the selection of the higher-level control unit. The BMS should be able to communicate with various higher-level control units without unnecessary restrictions.

The BMS must include a CAN interface for communication with a higher-level control unit. The baud rate of the BMS CAN interface needs to be configurable.

Firmware update -The BMS firmware should support updating via CAN, enabling easy installation updates.

Ethernet communication interface - Ethernet and TCP/IP enable higher data rates, allowing the BMS to communicate more measurement data to higher-level control units and other data processing units.

The BMS needs to include an Ethernet interface for TCP/IP communication with a higher-level control unit.

Modbus communication interface - Modbus communication is popular in industrial environments because it is openly published. It uses serial communication protocols to provide control and data acquisition through query and response between BMS master and slave modules.

The BMS should incorporate the Modbus interface for TCP communication with a high-level control unit.

Version identification and update - The BMS needs to be capable of communicating its version information. This will allow an operator or control unit to identify the supported features and capabilities associated with that version of the BMS.

The BMS must be able to report its version through the communication interfaces.

3.1.3. Optimization and control

Charging optimization—One of the important features of lithium-ion batteries is their fast-charging capability. However, this leads to fast aging. On the contrary, too slow charging creates a bottleneck for the widespread LIB application spectrum.
The Battery Management System (BMS) must optimize the charging rate based on the battery's chemistry to maximize charge-discharge capacity and extend its lifetime.

Balancing control—After charging cell balancing takes place with the battery pack. An imbalance occurs when each cell in the connected series of the battery pack has a different State of Charge (SOC). This imbalance leads to the overall battery capacity being equal to that of the weakest cell in the pack. To optimize battery life, it is important to ensure that cell balancing equalizes the overall battery state of charge of each cell in the pack.

The BMS shall be able to balance the individual cells in the battery pack with a specified maximum current.

3.1.4. Battery protection

Insulation monitoring - The BMS should measure the insulation status between the HV positive and chassis and between the HV negative and chassis. Insulation errors can result in potentially hazardous battery events. Continuous monitoring of insulation can help detect these issues early.

Over-charge/over-voltage protection - Lithium-ion batteries can be damaged if the maximum allowed voltage is exceeded, leading to hazardous chemical reactions. Thus, the BMS must detect and prevent overcharge and overvoltage events by shutting off contactors or limiting the discharging current and signaling the event to the higher-level control unit.

Over-discharge/under-voltage protection - Lithium-ion batteries are sensitive to undervoltage events. If the minimum allowed voltage is exceeded, hazardous chemical reactions may occur, potentially damaging the battery cell. So, the BMS must be able to detect potential over-discharge and undervoltage events. If such an event occurs, the BMS must prevent it (for example, by switching off contactors at specific limits or limiting the discharging current) and/or trigger it to the higher-level control unit.

Over-current protection - Drawing a higher-than-allowed discharging current from batteries can cause hazardous chemical reactions and damage the battery cell.

The BMS must detect and prevent overcurrent events, such as switching off contactors or limiting discharge current, and signal the event to the higher-level control unit.

Over-temperature charge-discharge protection - An over-temperature event during charge and discharging can result in battery failure. This could be due to cooling system issues, excessive heat in the operating environment, or high power levels. This overheating leads to detrimental chemical reactions in the battery, causing damage.

The BMS must detect and prevent over-temperature charge-discharge events and notify the higher-level control unit.

Under-temperature charge-discharge protection - An under-temperature event during both the charge and discharge can result in accelerated battery degradation. This could be due to cooling system issues or the operating environment being too cold. Like overheating, the too-cold operating temperature could lead to detrimental chemical reactions in the battery, causing damage.

The BMS must detect and prevent under-temperature charge-discharge events and notify the higher-level control unit.

3.1.5. Battery state estimation and performance

State of Charge (SOC) estimation - The application operator (either directly or through a higher-level control unit) must estimate the application's remaining runtime to plan the next steps of work. The state of charge is a key metric for supporting this planning.

The BMS is to estimate the battery's SOC and communicate it through the defined interface. The estimated SOC must account for changes in temperature, charge/discharge rate, and battery health. The communicated SOC values should not be below 0% or exceed 100%.

State of Health (SOH) estimation - The application operator (either directly or through a higher-level control unit) must estimate the application's current state of health to plan maintenance, for example. The state of health is one measure that aids in this planning.

The BMS must estimate the SOH of the battery subsystem. The estimated SOH must be communicated on the defined interface. The communicated minimum and maximum SOH values must not fall below 0% and must not exceed 100%.

State of Energy (SOE) estimation - The application operator (either directly or through a higher-level control unit) needs to estimate the application's remaining runtime to plan the next course of action. The SOE serves as one metric to facilitate this planning.

The BMS is responsible for estimating the battery's SOE and communicating it through a specified interface. The estimated SOE takes into account changes in internal temperature, charge/discharge rate, and battery health. The communicated SOE values range from 0% to 100%.

Remaining Useful Life (RUL) prognosis - The remaining useful life (RUL) refers to the amount of time that a battery can operate before it needs to be replaced. Estimating RUL is important for scheduling maintenance, optimizing operating efficiency, and preventing unplanned downtime. As a result, estimating RUL is a top priority in advanced ESS management programs.

The BMS needs to predict the RUL for both first-life and second-life batteries. The obtained RUL information must be communicated to the designated interface. The RUL value should be provided in terms of either the number of cycles or time duration.

3.1.6. Error mitigation and handling

Single Event Upset (SEU) recovery -The reliability of the BMS is crucial, and it's important to analyze SEUs in the control logic of the charge equalizer subsystem. SEUs occur when charged particles affect an embedded device, causing memory cells to change state. The BMS must detect and correct these bit-flips.

The BMS must be capable of isolating and recovering from SEUs to ensure its safe and effective operation.

3.2. Cloud based software and infrastructure

3.2.1. Safety

The integration of cloud-based software within the BMS will significantly enhance safety features, ensuring reliable and secure operation.

3.2.2. Remote and Predictive Maintenance

The cloud-based software layer will incorporate advanced capabilities for remote and predictive maintenance. This will allow for continuous monitoring and analysis of battery systems, identifying potential issues before they become critical. Predictive maintenance will reduce the likelihood of unexpected failures, enhancing overall safety.

3.2.3. Self-Diagnosis and Fault Detection

The software will include functionalities for self-diagnosis and fault detection. It will generate comprehensive reports on the health and status of battery systems, enabling timely and scheduled interventions. Fault detection algorithms running on the cloud will analyze vast amounts of data in real time, quickly identifying and addressing anomalies that could compromise safety.

3.2.4. Specific Safety Metrics and Requirements

Cell Voltages and Temperatures - Monitor and report individual cell voltages and temperatures continuously.

SOX (Battery State) - Include comprehensive state-of-charge, state-of-health, and state-of-function metrics.

Balancing Feedback - Provide real-time feedback on cell balancing operations.

Current Sensor Measurements - Include measurements of pack voltages at various points and current sensor data.

Hardware Information - Track and report hardware status and operational parameters.

Last State Request - Log and review the last state request made to the BMS.

Min, Max, and Average Values: Calculate and report minimum, maximum, and average values for voltages and temperatures.

Maximum Safety Limits (MSL) - Implement and monitor maximum safety limits for all critical parameters.

Recommended Safety Limits (RSL) - Ensure recommended safety limits are adhered to for optimal operation.

Maximum Operating Limits (MOL): Monitor and enforce maximum operating limits to prevent unsafe conditions.

BMS State: Report the current state of the BMS, such as standby, normal, or charge mode.

Current Limits: Calculate and enforce current limits based on the state-of-function.

3.2.5. Cloud-based Software Requirements

Focuses on establishing requirements for a cloud-based software layer within the Battery Management System (BMS). The primary goal is to create a robust, secure, and scalable architecture that supports advanced functionalities for both First Life (FL) and Second Life (SL) battery applications.

3.2.6. Cloud Computing

Table 3 Database Integration

Database Integration	
Functionality	• Store and retrieve data related to condition monitoring assessments
Requirements	• Use of a robust relational database management system (RDBMS) such as MySQL or PostgreSQL. • Implement ORM (Object-Relational Mapping) for database operations to enhance development efficiency and maintainability. • Ensure database security through encryption, regular backups, and access controls.

Table 4 Algorithm Deployment

Algorithm Deployment	
Functionality	• Ensure robust, scalable, and secure deployment of algorithms within the BMS
Requirements	**Data Preparation and Processing**: • Implement data cleaning and preprocessing pipelines to prepare raw data for analysis. • Use scalable data storage solutions to manage large datasets. **Machine Learning Model Integration**: • Deploy machine learning models using cloud-based frameworks like TensorFlow, PyTorch or KubeFlow, MLFlow for ML pipeline orchestration. • Ensure models are optimized for real-time inference to provide timely insights.

	Real-Time Data Analytics: • Implement cloud-based streaming data processing using tools like Apache Kafka or Apache Flink. • Use real-time analytics to monitor battery performance and predict potential issues. **Model Training and Updating**: • Set up automated pipelines for model training using historical data stored in the cloud. • Implement mechanisms for regular model updates and retraining to incorporate new data. **Scalability and Performance Optimization**: • Use cloud platforms to dynamically scale resources based on workload. • Optimize algorithms for efficient resource utilization to reduce computational costs.

3.2.7. Web Design and User Interface

Table 5 Responsive design

Responsive Design	
Functionality	• The web application must be accessible on various devices, including desktops, tablets, and smartphones
Requirements	• Use CSS frameworks like Bootstrap or Bulma to create a responsive design. • Adaptive layouts to ensure optimal viewing and interaction experiences across different screen sizes.

Table 6 User interface compnents

User Interface Components	
Functionality	• Provide a clear and intuitive interface for users to interact with the system

Requirements	• Implement reusable UI components using JavaScript frameworks. • Provide interactive charts and graphs for data visualization.

Table 7 Access to analytical results

Access to Analytical Results	
Functionality	• Users should be able to access results from the data analytics and machine learning modules.
Requirements	• Implement RESTful API endpoints using the Flask or FastAPI Python frameworks to fetch analytical results and current data. • Data caching mechanisms to reduce latency and improve response times. • Real-time data updates using WebSocket communication.

3.2.8. Communication Protocols

Table 8 MQTT Data comunication protocol

MQTT Data Communication Protocol	
Functionality	• The MQTT protocol will be used for real-time communication between the front-end application and the automation platform.
Requirements	• Secure MQTT connection using TLS/SSL for data encryption. • Authentication mechanisms to ensure that only authorized devices can publish or subscribe to topics. • Quality of Service (QoS) levels to guarantee message delivery according to the needs of the application.

Table 9 HTTP/HTTPS protocol

HTTP/HTTPS Protocol	
Functionality	• Implement HTTPS for secure data transmission.
Requirements	• Use SSL/TLS certificates to encrypt data. • Employ authentication and authorization mechanisms to protect endpoints.

3.2.9. Security Measures

Table 10 Data encryption

Data Encryption	
Functionality	• Ensure all data transmitted and stored is encrypted
Requirements	• Implement HTTPS for secure communication over the web. • Use AES (Advanced Encryption Standard) for data at rest and TLS (Transport Layer Security) for data in transit.

Table 11 Access control and authentification

Access Control and Authentication	
Functionality	• Restrict access to authorized users only
Requirements	• Use OAuthlib or Authlib for implementing OAuth 2.0 for secure authentication. • Implement Role-Based Access Control (RBAC) using Flask-Principal or FastAPI Users. • Integrate multi-factor authentication (MFA) using PyOTP for time-based one-time passwords (TOTP).

3.2.10. Computing Costs

Computing costs in a cloud environment are influenced by several critical factors, including storage requirements, processing time, and data transfer. Each of these elements contributes to the overall expense of running software in the cloud, and their impact can vary significantly based on the specific needs and usage patterns of the application.

3.2.11. Storage Requirements

To estimate storage costs, consider both the raw signal storage and additional algorithm storage requirements. Based on the provided data from the algorithm developers:

Table 12 Data storage requirements

Algorithm	Raw Signal Storage	Algorithm Storage	Total Storage (per instance)
SOC	<1 min	<1 MB	<1 MB
SOE	<1 min	<1 MB	<1 MB
SOH	<10 MB	<1 MB	<11 MB
SOP	1 MB	<1 MB	2 MB
SOS	<10 MB	<1 MB	<11 MB
RU1L	0.5 MB/battery chemistry + 0.1 MB/year	<1 MB	2.1 MB*
RU2L	0.5 MB/battery chemistry + 0.1 MB/year	<1 MB	2.1 MB*

*The calculation is based on the target of KPI O202 of developing DT for at least 4 different chemistries

3.2.12. Processing time

Processing time refers to the duration it takes for an algorithm or computational task to complete its execution. In the context of cloud computing costs, processing time is a critical factor because cloud service providers typically charge based on the number of computational resources consumed over time. This is often measured in terms of CPU or GPU usage per second, minute, or hour.

Table 13 Processing times

Algorithm	Processing time
SOC	< 1s
SOE	< 1s
SOH	< 1s
SOP	< 1s
SOS	< 1s
RU1L	< 1s
RU2L	< 1s

3.2.13. Data Transfer Costs

Data transfer costs are estimated by considering the volume of data transferred into and out of the cloud. In this case the total data volume is the sum of all raw signal and algorithm storage requirements

3.2.14. Future Public Battery Infrastructures

To ensure that forthcoming battery infrastructures are robust, secure, and compliant with regulatory standards, facilitating better management and utilization of battery systems the following requirements must be met.

3.2.15. Data Factory Approach

Develop a novel IoT architecture to handle BMS public infrastructures, facilitate seamless data exchanges between low-level, cloud-based, and battery passport public infrastructures, improve filtering, refining, and energy efficiency, ensure real-time monitoring capabilities, and integrate with existing systems for comprehensive data flow and processing.

3.2.16. Public Infrastructure Compliance

Provide real-time access to data on battery states (SoX), power set points, and remaining useful life, align with EU directives for regulatory compliance and standardization, ensure interoperability through standardized communication protocols, and design scalable infrastructure to accommodate growing data volumes and expanding battery networks.

3.2.17. Standardization and Interoperability

Develop a full SL-BESS Standardization Roadmap, harmonize self-diagnosis protocols for consistent diagnostics, standardize communication interfaces for seamless data exchange, and implement standardized safety protocols to ensure safe operation within public infrastructures.

3.2.18. Cybersecurity Measures

Use homomorphic encryption to protect data during transmission and storage, ensure secure data integration procedures to protect private information, implement strict access control measures to prevent unauthorized access, and conduct regular security audits to identify and address vulnerabilities.

3.2.19. Battery Passport Public Infrastructures

Ensure battery passports include information on identification, basic characteristics, performance statistics, a unique identifier (e.g., QR codes) for each battery, document and track the entire lifecycle of the battery for transparency.

3.3. Data acquisition, processing storage, and efficiency

Monitoring key battery parameters is the primary function of a battery management system (BMS), and a prerequisite for other functions. The essential parameters include voltage, current and temperature. Battery state (SOX) analyses and estimations such as state of charge (SOC) or state of health (SOH), safety protection systems such as over-charge, over-discharge, and over-current protection, as well as energy and information management systems are all fundamentally dependent on the reliable and accurate acquisition and processing of these physical signals from the battery [11].

3.3.1. Data Acquisition

The acquisition of key parameter signals is performed at different physical levels depending on the signal requirements. While the total current of a battery energy storage system is typically only measured at one point on a pack level, it is common to have multiple temperature measurement points at the string, module or even cell level to provide an accurate overview of the thermal state of the system. The voltage must always be measured at the level of individual cells or parallel groups, as the BMS must be able to detect any anomalies and prevent every cell from exceeding voltage safety limits [12]. Total pack voltage can be included as an additional measurement input or calculated using the sum of the individual cell or module voltages connected in series [13].

Cell signal acquisition is conducted through an Analog Front-End (AFE). In the context of automotive applications and large BESS, this process is typically managed by dedicated Integrated Circuits (ICs), such as the LTC6804 by Linear Technology Corporation, the BQ series from TI, or other comparable multicell monitoring circuits [11]. These ICs are engineered to deliver high accuracy, high common-mode rejection, and elevated sampling rates, which are critical for reliable performance [12].

The BIG LEAP system must provide sufficiently rapid and accurate data acquisition for advanced state estimation algorithms to meet the KPIs. To this end, the minimum data acquisition requirements for each signal are defined by the various requirements for state estimation algorithms running on the BMS. In the following tables, the signal acquisition requirements of the individual algorithm development partners are laid out.

For all signals, the smallest required resolution and highest required sample rate define the general requirement for the acquisition.

Table 14: Minimum Cell Voltage Acquisition Requirements

Algorithm	***Partner in Charge***	***Signal Resolution (V)***	***Sample Rate (Hz)***
State of Charge (SOC)	IKERLAN	0.005	1
State of Energy (SOE)	IKERLAN	0.005	1
State of Health (SOH)	BFH	0.001	1
	FHG	0.001	10
State of Power (SOP)	BFH	0.001	10 (higher is better)
State of Safety (SOS)	Bring	0.01	10
Remaining Useful First Life (RU1L)	IKERLAN	0.05	1
Remaining Useful Second Life (RU2L)	VTT	0.05	1

Table 15: Minimum Cell Temperature Acquisition Requirements

Algorithm	***Partner in Charge***	***Signal Resolution (°C)***	***Sample Rate (Hz)***
State of Charge (SOC)	IKERLAN	1	0.1
State of Energy (SOE)	IKERLAN	1	0.1
State of Health (SOH)	BFH	0.1	0.1
	FHG	0.1	0.1
State of Power (SOP)	BFH	0.1	0.1
State of Safety (SOS)	Bring	1	0.1
Remaining Useful First Life (RU1L)	IKERLAN	1	0.1
Remaining Useful Second Life (RU2L)	VTT	1	0.1

Table 16: Minimum Pack Current Acquisition Requirements

Algorithm	***Partner in Charge***	***Signal Resolution (C-Rate)***	***Sample Rate (Hz)***
State of Charge (SOC)	IKERLAN	0.01	0.1
State of Energy (SOE)	IKERLAN	0.01	0.1
State of Health (SOH)	BFH	0.1	0.1
	FHG	0.01	50
State of Power (SOP)	BFH	0.01	0.1
State of Safety (SOS)	Bring	0.1	10
Remaining Useful First Life (RU1L)	IKERLAN	0.1	0.1
Remaining Useful Second Life (RU2L)	VTT	0.1	0.1

3.3.2. Processing Storage

State estimation algorithms running on the BMS require memory for the algorithms themselves and any associated data such as lookup tables. In addition to the initial storage requirements of the algorithms, many of them require additional short- or long-term storage of sensor data and processed information. Algorithms estimating the State of Health or Remaining Useful Life of the battery are dependent on long-term historical usage data, which generally means that the data storage requirements grow as the system ages. The Big Leap project features two development approaches for the SOH estimation algorithm, one of which uses statistical usage data stored in histograms as opposed to time-series data, thus reducing the storage requirements.

The Big Leap BMS must provide enough processing storage for the state estimation algorithms, short- and long-term raw signal data, as well as processed data. The storage requirements defined by the individual algorithm developers are laid out in the following table. As the storage requirements for raw signal data are dependent on the sampling rate and resolution of said data, those requirements are defined in terms of the duration of the time-series signal to be saved. Signal storage given in Megabytes represents processed signal data.

The sum of the algorithm storage and signal storage requirements define the general system requirements. The raw signal storage can be shared by all algorithms and is defined by the largest individual requirement.

Table 17 Processing Storage Requirements

Algorithm	***Partner in Charge***	***Algorithm Storage***	***Signal Storage***
State of Charge (SOC)	IKERLAN	1 MB	1 min
State of Energy (SOE)	IKERLAN	1 MB	1 min
State of Health (SOH)	BFH	1 MB	10 MB (Not time-dependant)
	FHG	1	10 MB
State of Power (SOP)	BFH	1 MB	5 min
State of Safety (SOS)	Bring	1 MB	10 MB
Remaining Useful First Life (RU1L)	IKERLAN	1 MB	0.5MB per battery chemistry + 0.1MB per year of operation
Remaining Useful Second Life (RU2L)	VTT	1 MB	0.5MB per battery chemistry + 0.1MB per year of operation

3.3.3. Efficiency

To guarantee the safe and reliable operation of the battery system, certain algorithms must provide state estimations within near real-time. The State of Safety (SOS) is critical for any operating condition and must be continuously estimated with minimal delay. The State of Power (SOP) determines how much current may be drawn or accepted from the battery at any given time and must be continuously estimated during operation. The State of Charge and State of Energy are less time-sensitive than the previous two algorithms but must also be estimated continuously during operation. Finally, the State of Health and Remaining Useful Life algorithms don't need to be processed in real-time. In the following table, the processing time requirements of the individual algorithm developers are laid out.

Table 18 Requirements for maximum processing time

Algorithm	Partner in Charge	Maximum Processing Time (s)
State of Charge (SOC)	IKERLAN	1
State of Energy (SOE)	IKERLAN	1
State of Health (SOH)	BFH	No real-time requirement
	FHG	No real-time requirement
State of Power (SOP)	BFH	1

State of Safety (SOS)	Bring	1
Remaining Useful First Life (RU1L)	IKERLAN	No real-time requirement
Remaining Useful Second Life (RU2L)	VTT	No real-time requirement

4. Standards, regulation, life cycle assesment and sustainability

4.1. LCA requirements of sustainable BMS

The battery management system generally comprises five key components: battery module boards (BMBs), high-voltage and low-voltage systems, fasteners, and the integrated battery interface system (IBIS) [14]. These components consist of the electronic circuits, software, and both internal and external connections and wires necessary for the battery's operation.

The most widely accepted definition of sustainability among experts involves the integration of three pillars: environmental, economic, and social. The Life Cycle Sustainability Assessment (LCSA) typically combines and applies three distinct life cycle assessment approaches Environmental Life Cycle Assessment (E-LCA), Social Life Cycle Assessment (S-LCA), and Socioeconomic Assessment [15] [16].

According to the state of the art, different authors consider different weights for the BMS, ranging from 2 to 5% of the total weight of the battery pack. In terms of mass distribution within the BMS, printed wire (circuit) boards account for 10%, while steel and copper components make up 40% and 50%, respectively [17].

Other materials used in the BMS include gold, that is applied in the integrated circuit of the system and aluminium together with copper for the cables. Steel is used for the box of the BMS, and additional metals, such as, nickel, iron, tin in diverse components [5, 6]. The literature presents varied perspectives on the environmental impacts of the BMS. Some authors argue that the BMS contributes less than 20% of the total environmental impacts of the battery pack, while others suggest contributions reaching up to 40%, such findings show that this management systems should be further studied in terms of environmental impacts [17].

The key sustainability challenges, primarily stem from metal supply and energy-intensive processes. The main contributors for the environmental impact were aluminium, steel, copper, and gold. The major environmental impact categories affected included metal depletion, eutrophication potential, ozone depletion potential, ecological toxicity potential [17,18,19,20,21].

In order to mitigate the impacts associated with the metals used in the BMS, Table 19 outlines several Key Performance Indicators (KPI) aimed at reducing the impacts.

Various directives from the European Commission regulate many of the materials used in batteries. Examples include the Battery Regulation, the Critical Raw Materials Act, and the Conflict Minerals Regulation. These regulations have been adapted to the case of the BMS.

Under the Critical Raw Materials Act, 10 percent of critical materials are expected to come from EU countries, and a maximum of 65 percent will come from a single country outside the EU. These measures aim to improve the strengths and opportunities of the Single Market and the EU's external partnerships to diversify and enhance the resilience of the EU's critical materials supply chains [22].

The Conflict Minerals Regulation requires that the metals gold, tantalum, tin, and tungsten come from conflict-free zones and are sourced responsibly. The aim is to combat the financing of armed groups and improve the social conditions of communities that depend on the extraction of these metals [23].

Finally, the Battery Regulation establishes sustainability guidelines for batteries and their waste throughout their life cycle, ensuring they are safe, sustainable, and competitive [24].

Table 19 Recommendations to sustainable metals managment

Metric	Description	Value		Reference
Percentage originated from EU of strategic raw materials consumption (Critical Raw Materials Act)	Percentage of strategic raw materials originating from extraction within the EU compared to total consumption (2030)	nickel and copper	10%	[20]
Quantity of strategic raw materials originated from a single country (Critical Raw Materials Act)	Maximum percentage of strategic raw materials originating from a single third country, unprocessed or at any stage of processing (2030)		65%	[20]
Material Recovery **(Batteries regulation)**	Ratio of total amount of output useable materials by weight of input materials (2027) – entire battery system	Nickel	90%	[24]
		Copper	90%	
Recycling Efficiency **(Batteries regulation)**	Ratio obtained by dividing the mass of output fractions accounting for recycling by the	average weight of lithium-based batteries	65%	[24]

	mass of the waste batteries input fraction			
Carbon Footprint Declaration (Batteries regulation)	Report the total greenhouse gas emissions associated with the life cycle of the system			[24]
Other elements recovery targets (Batteries + Europe)	Targets for the recovery of key materials from recycling processes, promoting resource efficiency and reducing reliance on virgin materials (2027)	Aluminium	95%	[25]
Responsible sourcing of materials (Conflict Minerals Regulation)	The minerals and metals have to be sourced from conflict free countries	Tin and gold		[23]

Another strategy to improve the sustainability performance of the BMS involves optimizing the overall system performance rather than solely concentrating on material enhancements. While the BMS necessitates the use of cables, connectors, and harnesses to carry out its functions, these components are susceptible to malfunctions that can be challenging and costly to rectify [26].

An effort should be made to simplify the assembly and production of the BMS in the battery pack, leading to cost savings and reduced material usage while decreasing the system's impacts. Additionally, reducing the number of physical connections between the BMS and the rest of the battery pack would streamline the assembly process [26]. Furthermore, reducing the number of necessary components and materials in the BMS will free up space within the battery pack. This additional space can increase the number of battery cells or decrease the battery pack's overall size, depending on the design necessities [28].

Another way to enhance the sustainability of the BMS is by improving the accuracy and speed of its readings. Enhanced data accuracy allows for better prediction of the state of the battery components, facilitating quicker responses to potential issues. This proactive approach not only extends the lifespan of the battery but also reduces material waste and overall costs associated with battery maintenance and replacement [26].

Further improvements lie in the selection of materials used in the BMS. By opting for more suitable materials, the BMS can achieve better performance, conserve resources, and simplify the system. One innovative example is the use of silicon in the battery junction box [27].

Using second-life modules and integrating them into a BESS extends the battery's life, reducing and avoiding the impacts of producing new batteries for the BESS. Moreover, the BMS itself mitigates impacts by extending its lifespan through the system's modularity.

The BMS developed in the project should facilitate the integration of modules from various chemistries, enhancing practicality and minimizing the time required for disassembly and replacement. This approach not only reduces the impact on workers but also cuts down on development costs and allows for future upgrades or replacements. Regarding the end-of-life stage, the design should take into consideration the recycling phase. By reducing the number of materials and connections and ensuring ease of disassembly, the recycling process becomes significantly more efficient and desirable.

The main points proposed to improve the sustainability performance of the BMS are as follows:

- Simplicity associated with the assembly and production of the battery pack
- Reduction in the use of cables, connectors, and harnesses
- Ease of obtaining analyses
- Decrease of battery size
- Increase of energy density of battery pack
- Improve the accuracy and timing of the readings
- Selection of superior materials in the BMS system

4.2. BMS Hardware compliance with norms and standards

4.2.1. CE conformity

The CE marking is mandatory for all products sold in the European Economic Area (EEA). It is a self-declaration that the product complies with all applicable EU harmonised standards and directives. The CE mark means that the manufacturer affirms the equipment's conformity with European health, safety, and environmental protection standards. It indicates that the product may be freely traded in any part of the EEA regardless of its country of origin.

In order to obtain CE conformity for the developed BMS and BMS, the following EU directives should be followed:

- 2014/35/EU - Low voltage
- 2014/30/EU - EMC directive
- 2011/65/EU ROHS-recast directive

4.2.2. Low voltage directive

The Low Voltage Directive (LVD) 2014/35/EU refers to the legislation that ensures that electrical equipment and components below 1 kV AC and below 1.5 kV DC provide a high level of protection within the EU health and safety requirements. The LVD covers electrical safety requirements for the system level and for all electrical components of the BESS. The main hazards covered by the LVD are electric shock and short circuit.

To prove compliance with the LVD, one can use harmonised standards.

The following harmonised standards are of specific relevance to prove compliance with the LVD for the BMS, the BPU and a BESS in general:

- HD IEC 60364 - Low-voltage electrical installations (All parts)
- EN IEC 60664-1:2007 - Insulation coordination for equipment within low-voltage systems - Part 1: Principles, requirements and tests
- EN IEC 60664-4:2005 (Required) - Insulation coordination for equipment within low-voltage systems - Part 4: Consideration of high-frequency voltage stress
- EN IEC 61140:2016 (Required) - Protection against electric shock - Common aspects for installation and equipment

4.2.3. EMC directive

Electromagnetic compatibility (EMC) describes the ability of electronic and electrical systems or components to function correctly when they are in close proximity to each other, by limiting their mutual electromagnetic disturbances (i.e., emission levels). It is also vital that each component has sufficient level of immunity to the disturbances in its working environment.

The EMC Directive 2014/30/EU ensures that electrical and electronic equipment used in EU does not generate or is not affected by electromagnetic disturbance. The EMC Directive is hence a legislation governing the immunity of equipment to interference and the electromagnetic emission threshold of these equipment. To ensure the correct operation of a stationary BESS, the electromagnetic compatibility guidelines cover any issues relating to disturbances between components of a BESS from both external and internal sources as well as emitting disturbance to the outside of the BESS. Specifically, PE, communication busses, EMSs and BMSs require audits by recognized and certified institutes.

To prove compliance with the LVD, one can use harmonised standards.

The following harmonised standards are of specific relevance to prove compliance with the LVD for the BMS, the BPU and a BESS in general:

- EN IEC 61000-6-2 - Electromagnetic compatibility (EMC) - Part 6-2: Generic standards - Immunity for industrial environments
- EN IEC 61000-6-4 - Electromagnetic compatibility (EMC) - Part 6-4: Generic standards - Emission standard for industrial environments
- IEC 61326-1 - Electrical equipment for measurement, control and laboratory use - EMC requirements - Part 1: General requirements

- EN IEC 61000-6-1 - Standard for Electromagnetic compatibility (EMC) - Part 6-1: Generic standards - Immunity standard for residential, commercial and light-industrial environments
- EN IEC 61000-6-3 - Standard for Electromagnetic compatibility (EMC) - Part 6-3: Generic standards - Emission standard for residential, commercial and light-industrial environments

In this list, EN IEC 61000-6-2 specifies the standards for electromagnetic immunity requirements of BESS and its components in an industrial environment.

4.2.4. Relevant Industrial norms for BESS and BMS

While a CE declaration of conformity is a legal requirement in order to be able to sell a system in the European Economic Area, other industrial norms are also relevant to ensure safety and quality of BESS, BMS and BPU.

- IEC 62619:2022 - Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries, for use in industrial applications.
- IEC 62485-2:2010 - Safety requirements for secondary batteries and battery installations – Part 2: Stationary batteries.
- IEC 62933-5-1:2017 - Electrical energy storage (EES) systems - Part 5-1: Safety considerations for grid-integrated EES systems - General specification.
- IEC 62933-5-2:2019 - Electrical energy storage (EES) systems - Part 5-2: Safety requirements for grid-integrated EES systems - Electrochemical based systems.

Specifically, for the BMS, IEC62619 defines the need for the BMS to comply with functional safety. The following norms are therefore relevant to ensure the BMS is design with the correct functional safety:

- IEC 61508 (all parts)
- Annex H of IEC 60730-1:2020
- ISO 13849 (all parts)

Specifically for determining the functional safety requirements of the BMS, IEC62619 mentions the need to execute a risk assessment and mitigation of hazards (e.g., FTA, FMEA) process. This process should be done in coordination with the end-use equipment manufacturer in order to fully cover the spectrum of risks.

The procedure is as follows:

a. hazard analysis.
b. risk assessment.
c. safety level target (e.g., safety integrity level (SIL) target.

IEC 62619 then requires the BMS to be designed according to the safety integrity level (SIL) target defined in point c) above.

On top, IEC 62619 mentions the tests to execute to evaluate the BMS charge control:

- **Overcharge control of voltage (battery system):**
    - The BMS shall control the cell voltage during charging below the upper limit charging voltage of the cells.
- **Overcharge control of current (battery system):**
    - If the charging current of the cells in the battery system exceeds the maximum charging current of the cells the BMS shall interrupt the charging to protect the battery system from hazards related to charging currents above the specified maximum charging current of the cells.
- **Overheating control (battery system):**
    - The BMS shall terminate charging when the temperature of the cells in the battery system exceeds the upper limit that is specified by the cell manufacturer.

4.3. BMS and ESS scenarios and development in standards and guidelines

The analysis considers standards and regulations. We will review existing standards such as ISO 26262, UL1973, UL2271, UL9540, IEC 62619, ECE R100 Rev3 / UNR100, UL2580, and AUTOSAR. The goal is to identify where these standards can be improved for SL-BESS, where specific challenges like ageing effects, charge capability, operation temperature, cell balancing, and varied cell histories must be addressed.

The proposed standards will be developed based on the Siro's first life battery user manual and this proposed standard will ensure that the installation and commissioning of SL BESS is practical, efficient, easy and safe in various environments.

Monitoring and control protocols are crucial for managing battery health and performance. SIRO assesses current protocols to pinpoint deficiencies in real-time data acquisition and predictive maintenance capabilities. Proposed enhancements aim to ensure more accurate and timely monitoring, which is vital for maintaining the longevity and reliability of battery systems.

One more aspect to focus on is maintenance and service procedures. The existing maintenance schedules and service procedures are being evaluated to understand their limitations, mainly when dealing with ageing batteries and SL-BESS. SIRO suggests implementing more robust and adaptive maintenance strategies to meet these systems' changing needs.

Environmental and sustainability standards are examined to ensure that batteries' overall impact throughout their lifecycle, including disposal and recycling, is adequately addressed. Current standards, such as IEC 62619, are carefully assessed for deficiencies, and new standards are suggested to encourage more sustainable battery management practices.

The smooth operation of BMS and SL-BESS needs interoperability and compatibility between different battery systems and components. SIRO will assess the current interoperability state and identify compatibility limitations between first-life and second-life batteries. The goal is to propose standards to ensure seamless interoperability across different platforms and technologies.

Reviewing certification and compliance processes to ensure they are sufficient for emerging technologies. We will evaluate existing certifications such as UL9540 and ECE R100 Rev3 and recommend updates to accommodate new advancements in battery technology.

Identification of Gaps and Limitations:

SIRO's analysis has identified several gaps and limitations in the current standards for SL-BESS. These include coverage gaps related to unique challenges such as ageing effects, degradation behaviours, and varied cell histories that still need to be fully addressed. The analysis also highlights the need for guidelines for adapting current standards to reconfigure and repurpose SL-BESS and addressing interoperability issues, such as compatibility between different battery types, brands, and chemistries and between first-life and second-life batteries.

Evaluation of Advantages:

Despite some gaps and limitations, the current standards provide significant advantages. Aligning project outputs with established standards improves BMS and ESS technologies' safety, efficiency, and market acceptance. The project also has the potential to develop innovative compliance testing methods specific to SL-BESS, addressing gaps in current regulations. Furthermore, by proposing solid standards, the project can promote broader market adoption and integration of advanced BMS and SL-BESS technologies.

Proposed New Recommended Standards:

SIRO will propose several new standards to address identified gaps. The standards for SL-BESS are being developed to provide guidelines for assessing, reconfiguring, and repurposing second-life batteries, ensuring safety and performance. Interoperability standards are also being created to ensure compatibility and seamless operation between different battery systems, including diverse chemistries and life cycles. Additionally, sustainability and recycling standards are being proposed to promote comprehensive environmental impact, recycling, and disposal practices, ensuring a sustainable battery lifecycle.

5. Conclusion

In the initial phase of the project, general requirements for the novel BMS system should have been established. An analysis of the system's structure and functionality revealed that in addition to the traditional requirements for a BMS system and its functionality, a flexible system like BIG LEAP introduces additional needs. The primary ones are:

- Compatibility of the BMS with a range of battery chemistries and suppliers.
- A more in-depth analysis of the state of health of battery cells.
- Flexibility in the organization of the multilevel control system.
- Compatibility with a broader range of communication protocols and data structures.

In an effort to provide a comprehensive review and cover all aspects of operations, hardware and software requirements and recommendations are described in dedicated chapters but in addition extended with description of the battery system structure, interfaces, use cases, and standards recommendations to create complete view.

These requirements and recommendations should be taken as a starting point, but they will be developed into a detailed specification as the BIG LEAP system development and testing progresses.

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