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BATTERY2LIFE

D3.1 BMS E/E topologies

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LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation	Meaning
ADC	Analog-to-Digital Converter
AES	Advanced Encryption Standard
AI	Artificial Intelligence
API	Application Programming Interface
BJB	Battery Junction Box
BLE	Bluetooth Low Energy
BMS	Battery Management System
BS	Battery System
CAN	Controlled Area Network
CRC	Cyclic Redundancy Check
DC	Direct Current
E/E	Electrical / Electronic
ECM	Equivalent Circuit Model
EIS	Electromechanical Impedance Spectroscopy
EV	Electric Vehicle
FW	Firmware
HAL	Hardware Abstraction Layer
HV	High Voltage
HW	Hardware
I2C	Inter-Integrated Circuit
IC	Integrated Circuit
IMD	Insulation Monitoring Device
IP	Intellectual Property
LIB	Lithium-Ion Battery
MAN	Metropolitan Area Network
MCU	Microcontroller
MMS	Module Management System
NFC	Near Field Communication
PCB	Printed Circuit Board
RF	Radio Frequency
SoC	State-of-Charge
SoH	State-of-Health
SoT	State-of-Temperature
SoW	State-of-Warranty
SoX	State-of-X (involving all estimators)
SPI	Serial Peripheral Interface

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SW	Software
UART	Universal Asynchronous Receiver/Transmitter
VPN	Virtual Private Network
WAN	Wide Area Network
WLAN	Wireless Local Area Network

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EXECUTIVE SUMMARY

The objective of Task 3.1 in work package 3 was to define the different electrical/electronic (E/E) topologies for each of the two pillars within the Battery2Life project. While both pillars share the common goal of enabling a smooth transition of battery system to their second-life, their use cases and corresponding requirements differ. Pillar 1 is centred around grid-scale applications, whereas Pillar 2 focuses on residential energy storage for photovoltaic systems. These differing use cases result in variations in the E/E topologies, which is why most chapters in this deliverable contain dedicated subchapters for each pillar.

The first chapter deals with the general Hardware (HW) topologies, consisting of the overall architecture, the battery management system (BMS), the module management system (MMS) the battery junction box (BJB) and various other parts of a battery system and how they relate to each other. Pillar specific details such as active balancing are also included in this chapter.

The second chapter addresses the wireless communication between BMS and MMS. A brief overview of the advantages and disadvantages is given, and the latest technologies are introduced. Each pillar presents its own solution how to implement this feature, to improve the disassembly and reassembly process for 2nd life applications.

The third chapter is specific for Pillar 1 where electrochemical impedance spectroscopy (EIS) measurements to obtain detailed information about the actual state of the battery are introduced.

The final chapter focuses on cloud communication. In both pillars, the BMS interacts with the cloud, enabling real-time monitoring, control, and management of second-life battery systems. This centralized approach consolidates data from distributed BMS units, allowing advanced cloud-based algorithms to provide highly accurate battery state estimations.

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1 INTRODUCTION

This section presents the project introduction, the purpose of the deliverable, the intended audience, and the structure of the deliverable.

1.1 Project Introduction

BATTERY2LIFE is a project, funded by the Horizon Europe programme that will facilitate the smooth transition of batteries to 2nd life use and 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. Figure 1 illustrates the Battery2Life solutions.

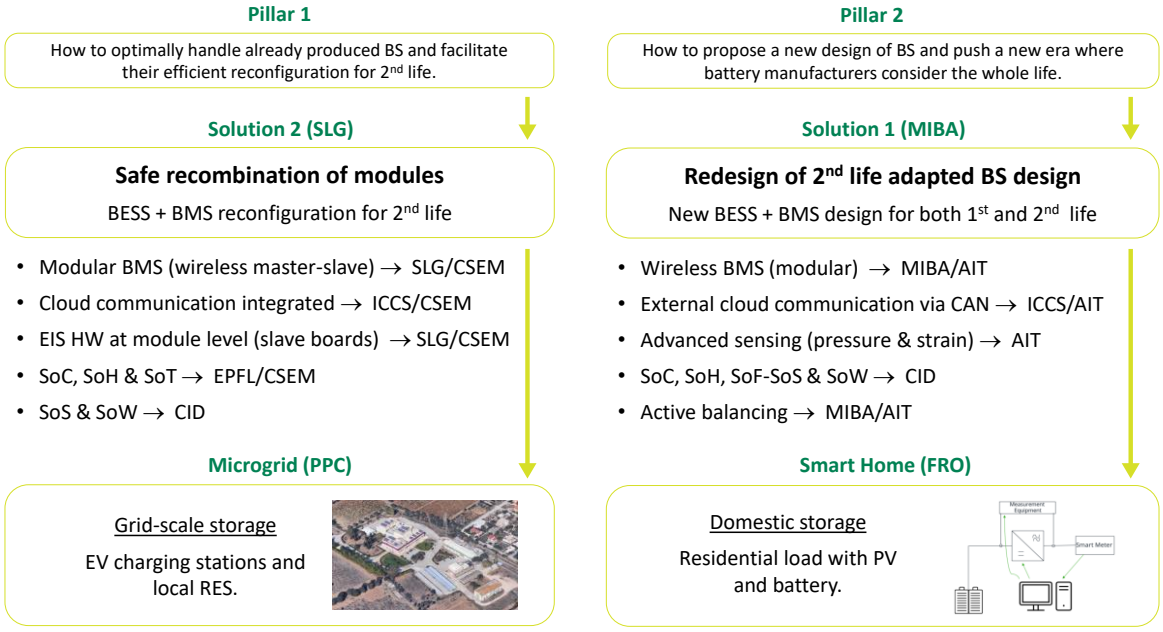

Figure 1: Battery2Life solutions.

Battery2Life introduces two new battery system design frameworks serving the upcoming market needs: the first supports the business transition for the initial market by remanufacturing based on existing battery systems while the second one introduces completely new design principles for 1st and 2nd life of the battery. Furthermore, Battery2Life introduces innovative embedded sensing and more accurate SoX (State-of-X) estimation algorithms, new SoX indicators appropriate for 2nd life use -i.e. SoS (State-of-Safety) and SoW (State-of-Warranty) - and a new EIS (Electromechanical Impedance Spectroscopy) implementation approach by integrating it in the BMS, that will enable the detailed safety and reliability monitoring at both cell and module level during 1st and 2nd life usage. The project will specify an open BMS concept, data formats, considering and extending the

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battery passport concept, and 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: The industrial (grid-scale) and domestic storage (Pillar 1 and Pillar 2), with respect to their operational specificities and requirements.

1.2 Purpose of the deliverable

The purpose of this deliverable is to introduce the E/E topologies and several advanced technologies that will be integrated into the novel battery system developed for 2nd life for both pillars.

The groundwork of both battery systems is given in this deliverable, therefore contributing to almost all the objectives and outcomes of this project. In particular it contributes to the **Expected Outcome 1**, by an open and interoperable BMS architecture enabling the adaptability to cover the requirements of different battery technologies. Furthermore, it contributes with the EIS implementation to **Expected Outcome 2**, enabling detailed safety and reliability monitoring at both the cell and the module level. Lastly, by integrating wireless communication between the BMS and MMS, it facilitates easy adaptability and reconfiguration for second-life applications, thereby contributing to **Expected Outcome 3**.

The following three key performance indicators (KPIs) where Deliverable D3.1 is expected to contribute the most are:

- **KPI 1:** 25% less time needed to manufacture the 2nd life batteries ESS when using the project enablers compared to without the enablers.
- **KPI 4:** Early detection of thermal runaway.
- **KPI 6:** 20% improvement in reliability of EV battery state assessment when using the innovative SoX algorithms and the diagnostic tool compared to conventional assessment methods.

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1.3 Intended audience

The intended audience for this public deliverable includes industry professionals, researchers, and policymakers interested in battery technology and energy storage systems. It targets engineers and technical experts who will find value in the detailed descriptions of electrical/electronic topologies of the novel approach to design a battery management system for second-life usage. Researchers and academics may focus on the innovative methods, while policymakers will gain insights into how the project supports sustainability and the circular economy.

1.4 Structure of the deliverable/correlation with other WPs

The deliverable consists of the following previously described main sections:

- **Section 2 – Definition of the Electrical and Electronic topologies**
- **Section 3 – Wireless Battery Management System**
- **Section 4 – Embedded EIS Configuration on Advanced BMS Slaves**
- **Section 5 – Cloud Communication**

This deliverable serves as the foundation for two subsequent tasks within the same work package. Task 3.2 will focus on the complete development of the wireless BMS, while Task 3.4 will cover the development of the embedded EIS configuration.

Additionally, it is closely tied to WP4 - *BMS algorithms and smart embedded functionalities*, where algorithms based on the advancements for the novel second-life BMS introduced in this deliverable are implemented.

In WP 5 - *BMS SW and HW integration and validation* the developed HW and SW are integrated, and the overall system is validated and scaled up. This deliverable lays the groundwork for the two demonstrator battery systems to be developed in this work package.

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2 DEFINITION OF E/E TOPOLOGIES

To ensure a uniform definition of the various technical terms used in the context of battery systems, the following is a brief description of the naming conventions used throughout the document:

- **Cell**: The smallest unit of the system.
- **Battery/Module**: Formed by cells connected in series or parallel.
- **String**: Created by connecting multiple batteries/modules in series.
- **Battery Pack**: Consists of multiple strings connected in parallel.

The **Electrical/Electronic (E/E) systems** that manage the safe and reliable operation of battery systems are typically arranged in a modular **Master/Slave** concept. These systems are defined as follows:

- **MMS (Module Management System)**: This so-called slave unit is responsible for managing individual battery modules.
- **BMS (Battery Management System)**: The master unit that oversees the entire battery system and communicates with the MMS units for system-wide control.

2.1 HW Topology: Pillar 1 Analysis

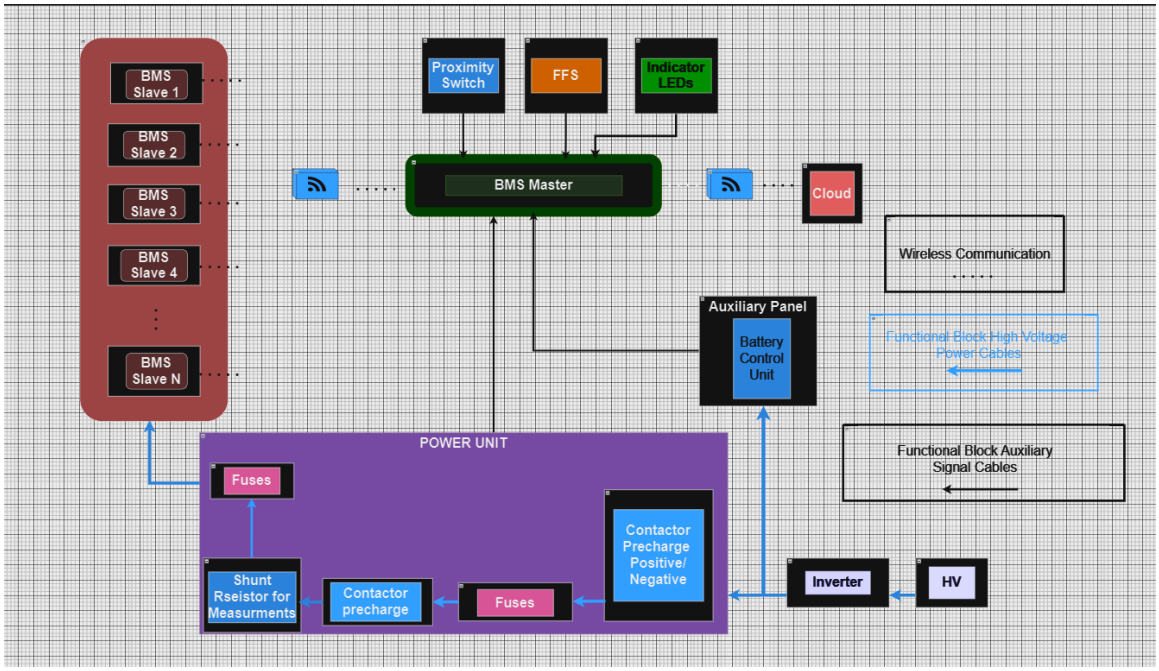

Figure 2: Functional Overview of ESS Structure with Wireless Communication

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Figure 2 provides a functional overview of this modular architecture, illustrating how wireless communication links are used to connect the BMS with the MMS units, ensuring real-time data flow and centralized management. This topology is adaptable to various pillars, including electric vehicles, renewable energy storage systems, and industrial applications, enabling flexible scaling and integration based on the specific needs of each pillar.

For instance, in the context of electric vehicles, the BMS Master manages crucial functions such as battery state monitoring, thermal management, and fault detection, while the MMS units handle individual modules, ensuring uniform performance across the system. Similarly, in industrial energy storage applications, this modular structure allows for easier maintenance and expansion by integrating additional modules without significant changes to the overall architecture.

BMS Master

The Master BMS functions as the central control unit for the battery system. It is responsible for:

- Monitoring: It collects data from multiple BMS slave units, which are distributed across various sections of the battery pack. It also monitors the current flowing through the whole pack.
- Controlling: Based on the data it receives, the master unit can:
    - Manage cell balancing to ensure uniform charge and discharge across battery cells.
    - Monitor state of charge (SoC), state of health (SoH), and battery parameters.
    - Trigger safety mechanisms (e.g., disconnecting circuits in case of overvoltage or overcurrent events).
- Communication: The master unit communicates with both internal and external systems, including:
    - Internal communication: Wireless links to the slave units for real-time data acquisition and control.
    - External communication: Wireless communication to external systems, like the cloud, for remote monitoring, firmware updates, and telemetry.
- Key Components of the Master BMS:
    - Microcontroller/Processor: Manages all operations within the system.
    - Power Distribution: Interacts with high-voltage (HV) power systems, fuses, current sensors and contactors.
    - Interface Modules: For communication with MMS, auxiliary panels, and cloud infrastructure.

- In this BMS topology, each **MMS** or also called a **BMS Slave Unit** is connected to a specific group of battery cells. The MMS plays a crucial role in monitoring, data transfer, and fault

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detection for its assigned cells, particularly with the integration of **Electrochemical Impedance Spectroscopy (EIS)** for advanced diagnostics. Below is a breakdown of the BMS Slave unit's functionality.

Module Management System

- Each MMS is responsible for continuously monitoring the health and status of its designated group of battery cells. This involves:
- **Voltage Measurement**: Tracking the voltage levels of individual cells to ensure they are within safe operating limits.
- **Temperature Monitoring**: Monitoring the temperature of the cells to avoid overheating, which could lead to cell degradation or thermal runaway.
- **Impedance Analysis (EIS)**: Using EIS, the MMS performs in-depth diagnostics of the battery cells, providing detailed insights into cell health, degradation, and remaining life.

The STM32 microcontrollers best suited for this purpose include:

- **STM32G4**: Offers real-time performance for precision sensing and control, making it suitable for EIS applications.
- **STM32F3**: Equipped with high-performance analog features, including ADCs, suitable for monitoring voltage, temperature, and impedance.

Battery Junction Box Safety Components

The Battery Junction Box (BJB) plays a crucial role in ensuring the safety and protection of the battery system, housing multiple key components that safeguard against faults and abnormal conditions:

- **Fuses:** Fuses are designed to protect the battery system by disconnecting circuits in the event of an overcurrent situation. When the current exceeds a specific threshold, the fuse blows, cutting off the electrical path and preventing damage to the system components.
- **Contactors:** Contactors are heavy-duty relays that control the connection between the battery and external systems like the powertrain (e.g., inverter and motor). They are essential for safe operation, allowing the Master BMS to connect or disconnect the battery from the powertrain when necessary, such as during startup, shutdown, or in response to a detected fault.
- **Pre-charge Circuit:** The pre-charge circuit ensures a smooth transition during system startup by limiting the inrush current to the high-voltage components. Without this circuit, the sudden connection of a high-capacity battery to the powertrain could result in a large inrush of current, potentially damaging sensitive components. The pre-charge

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circuit gradually increases the voltage to the operating level, protecting the system during startup.

- **Shunt Resistor:** The shunt resistor is used for precise current measurement in the battery system. By measuring the small voltage drop across the shunt resistor, the BMS can calculate the current flowing through the circuit. This is critical for monitoring the battery's SoC and SoH, as well as detecting any abnormal current conditions that could indicate potential issues within the system.
- **Insulation Monitoring Device (IMD)**: The IMD continuously monitors the insulation resistance between the high-voltage system and the vehicle chassis to detect any insulation faults. An insulation fault could create a hazardous situation, such as a short circuit or electric shock risk. The IMD helps ensure the system's safety by detecting these faults early, allowing for preventive action to avoid serious incidents.

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2.2 HW topology Pillar 2

Schematic of the overall design

Figure 3 illustrates the overall design concept of the EE architecture used in Pillar 2.

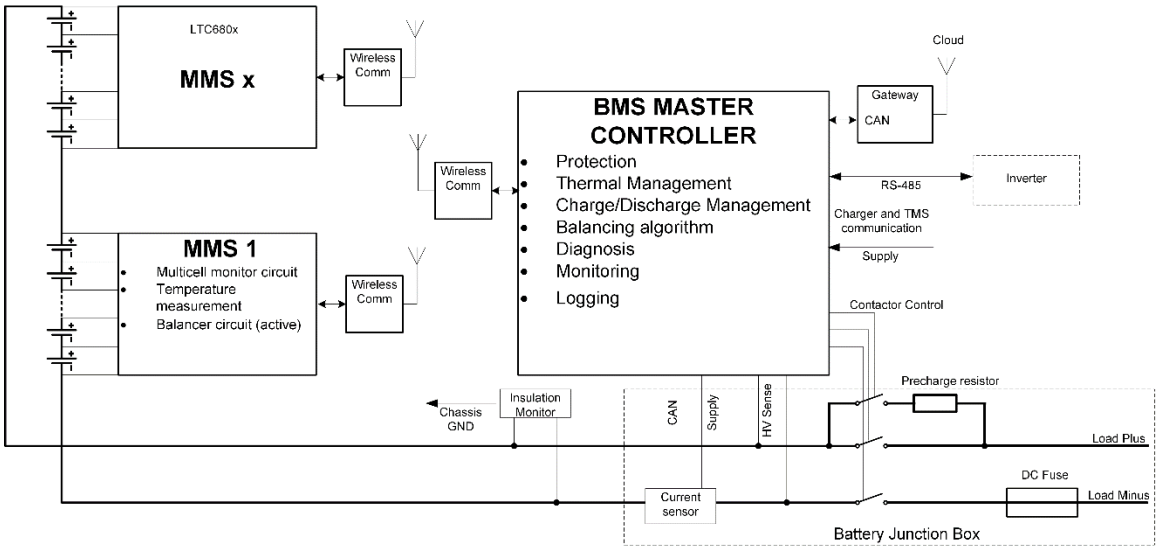

Figure 3: Schematic of the overall design of pillar 2

As depicted, the design is modular, with several Module Management System PCBs functions as slaves and a higher-level Battery Management System PCB as master.

The slaves are responsible for monitoring the voltage of every cell of the battery pack. As many cells are connected to form a string and the voltage monitoring chip on one MMS can only monitor a limited number of cells, there will be specific number of MMS boards depending on the application/battery system. In addition to their role as voltage monitors, the MMS also have the task of measuring the temperature at defined points inside the battery system as well as integrating the circuitry for actively balancing the cells.

The Battery Management System is an additional PCB which is configured as Master. It collects all the necessary data from the MMS slaves over a wireless communication interface (more on that in later chapters). The data is processed and used for the balancing algorithm, charge/discharge management, thermal management, protection, diagnostics and logging.

In addition to its internal tasks, the BMS is also responsible for various external security functions, and it communicates with different devices that are part of the overall system. It has the control over the switching of the contactor and pre-charging resistor which are located inside the battery junction box. The DC lines are being evaluated regarding their voltage and current values to guarantee the safe operation in acceptable ranges. The inverter between the photovoltaic panels

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and the battery receives data on the battery's state and health from the BMS over CAN/RS-485 so it can adjust its charging/discharging behaviour based on that data. This interaction helps to protect the battery, maximizes its lifespan and ensures that the system operates as intended. The last communication link is a gateway realized with CAN between the BMS and the cloud for remote monitoring, updates of SoX parameters, predictive and forecasting services (e.g. SoW).

Battery Junction Box

The Battery junction Box (BJB) is the switching and controlling unit of the BMS. It connects and disconnects the battery from the load, and it measures the systems current as well as several output voltages to ensure proper functionality. The BJB for Pillar 2 will be developed for the following battery pack specifications:

- Pack voltage: 243V (minimum), 295,2V (maximum)
- Pack current: 100A (continuous), 300A (peak)

The BJB consists of the following main components:

- Contactor to disconnect the pack from the load.
- Pre-charging resistor and contactor to pre-charge the load.
- Fuse to handle massive overcurrents or short circuits.
- Current sensor to measure the pack current.
- Voltage sensors to measure the pack voltage before the main fuse and after the contactors.
- Insulation measurement circuit to measure the insulation resistance between the high voltage potentials (Load plus, load minus) and the housing or chassis GND.

Active Balancing

There are several approaches to achieve active balancing between cells. They usually have the energy storage in form of magnetic fields in passive, inductive elements in common.

MIBA and AIT decided to use the balancer chip ETA3000 for Battery2Life due to its ease of use, affortability, the small footprint and its safety features. Figure 4 shows an exemplary circuit including the active balancing chip, extracted from its datasheet. The basic principle lies again in the current exchange from one cell to another through the energy storage in form of magnetic fields in the inductive element. In contrast to passive balancing methods, where the excess energy gets dissipated in form of heat over resistive components, the active balancing allows much higher efficiency (around 92%) due to its switching behaviour with energy storage. In addition to increased efficiency, the time required for balancing can also be reduced, as the current is not limited by the maximum power dissipation of the package of a resistor. The balancing current can be set through an external resistor to values up to 2A. This is possible through the adaption of the average inductor current.

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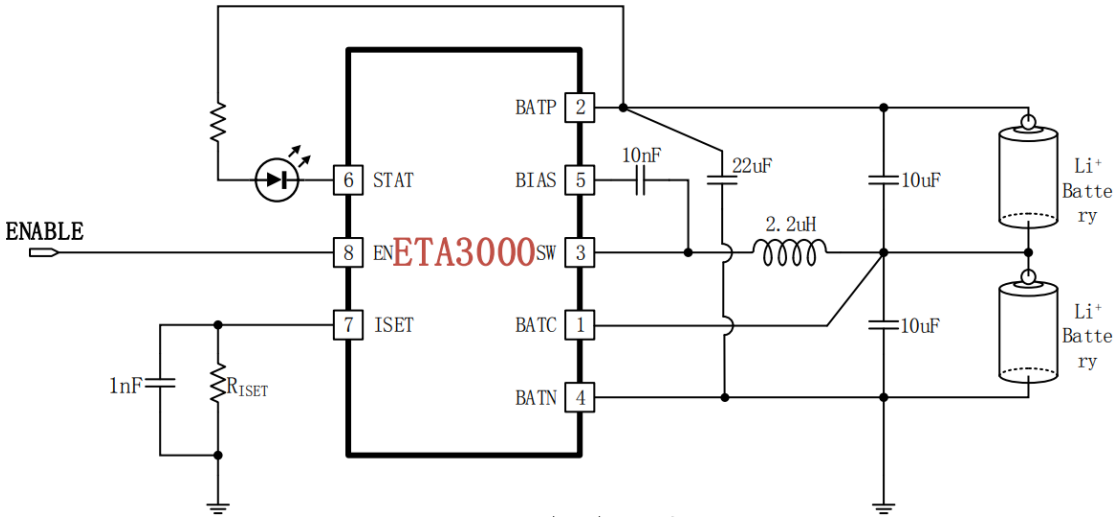

Figure 4: Exemplary active balancing circuit [1]

The ETA3000 works with ETA's proprietary technology utilizing a control scheme that balances two battery cells per IC up to +-30mV voltage accuracy VERROR. It detects the voltage difference between two adjacent cells and starts balancing when it hits the unbalance detection threshold VKICK = 100mV. As there are several safety mechanisms integrated, the cell voltages are additionally checked for over-/undervoltage conditions before the balancing algorithm starts.

When the measured voltage exceeds VKICK, the ETA3000 will discharge the higher voltage cell, store that energy in the inductor and finally charge the lower voltage cell. This process gets repeated until there is no voltage difference left (up to the mentioned voltage accuracy VERROR).

Once it reaches a balanced state, the ETA3000 automatically enters sleep mode, significantly reducing its energy consumption (current draw of typically 2µA), thereby preventing unnecessary drainage of the battery pack.

As this operation needs to be properly controlled, the ETA3000 has a clever state machine, which keeps the balancing safe. The Figure 4 shows the stage machine diagram which coordinates the internal process. When the battery is plugged in, it always starts from the "check state".

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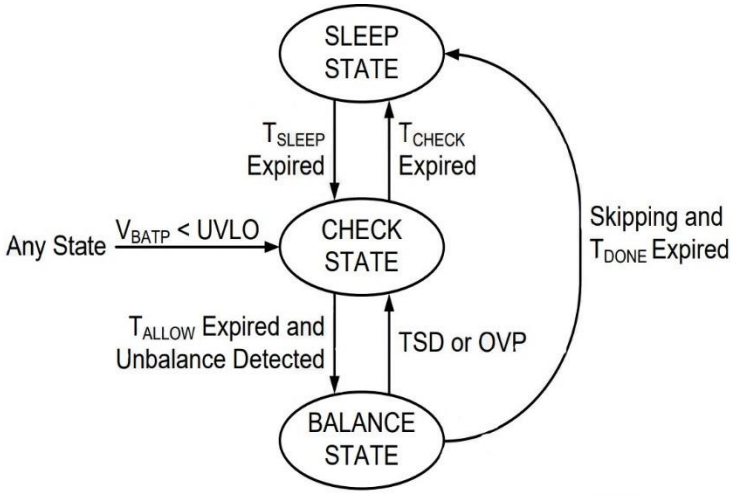

Figure 5: State machine diagram of the ETA3000 [1]

The superimposed timing profile is shown in detail in Figure 5. If the ETA3000 is enabled (internally pulled to logic HIGH), it checks every 2 seconds for an unbalanced state, otherwise it goes back to sleep mode. When unbalanced cells are detected and the safety buffer timer T_{ALLOW} (3.85ms) is expired, it goes into the "balance state". If the upper cell voltage is higher, the balancing will be "down", meaning that there is energy flow from upper cell down to the lower cell. If the bottom cell voltage is higher, balancing is "up" and the energy is moved to the upper cell.

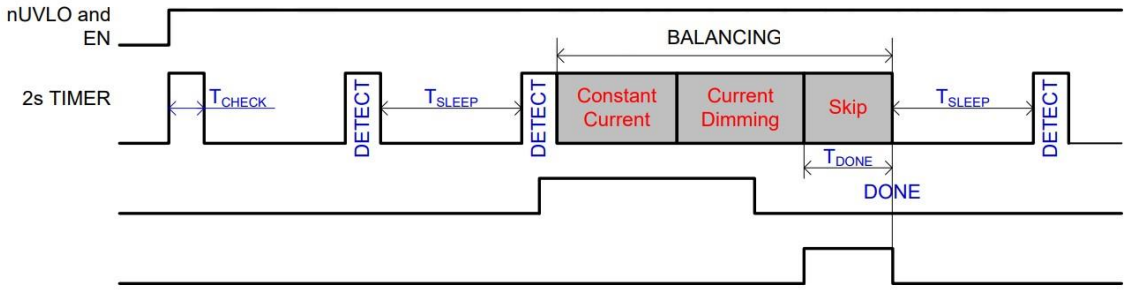

Figure 6: Timing profile for the state machine [1]

Figure 6 provides a zoomed-in overview of the balancing state as seen in Figure 5. The balancing always starts with a constant current phase since there is the highest voltage difference. The value is set externally through a resistor at pin I_{SET}. The MMS is equipped with a resistor value which allows balancing with maximum current of 2A. As soon as the voltage difference reaches almost zero, it goes into current dimming where the current is slowly reduced until the two cell voltages are equal. When this final condition persists for a time interval of T_{DONE} = 62ms it stops and goes back to sleep mode.

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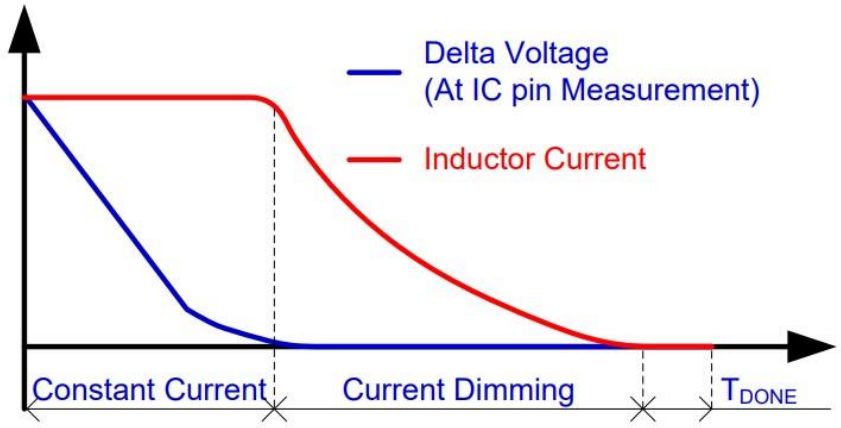

Figure 7: Balancing profile [1]

As the balancing is a safety-critical aspect of the E/E-concept, it is important that the ETA3000 incorporates protection mechanisms for exceptional conditions. These protection features include:

- Short and low voltage protection: when either of the cell voltages is below VPRECOND = 2.8V (rising, hysteresis 150mV falling), the maximum balancing current will be adjusted to 10% of the current set by the resistor at pin ISET.
- Open and over voltage protection: when either of the cell voltages is greater than V_{OVP} = 5V (rising, hysteresis 350mV falling), the balancing will be stopped and the ETA3000 goes back to the sleeping state.
- Thermal shutdown: when the part gets hotter than 160°C, it will stop the balancing and go back to its sleeping state.
- Current limit: the maximum allowable peak of the inductor current is 5.5A.

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2.3 Software architecture Pillar 1

The Software (SW) architecture for Pillar 1 was presented in D1.3 [D1.3 BMS Specifications and Advanced Algorithms for 2nd Life] of B2L project. To facilitate understanding, the principles are repeated below:

"The proposed SW architecture for the Pillar 1 is divided in three macro blocks: BMS Master; BMS Slaves and a Cloud Server.

The most fundamental design principles of the BMS architecture are clear interface definitions and a separation between HW dependent basic software (firmware, FW) and HW independent application software (SW), i.e. and AUTOSAR architecture. On multiple levels the BMS is conceived as a set of blocks that communicate with each other via clearly defined input and output data structures, also referred to as buses.

The cloud and the edge BMS communicate with one another via REST APIs (Application Programming Interfaces). The data structures of each endpoint are fixed, while the algorithms that take these data structures as input are interchangeable. On a hardware level, the communication between the BMS master and the cloud happens wirelessly. More precisely a Wi-Fi-capable chip on the edge BMS is connected to a 4G router that accesses the server network via a VPN.

At the BMS Master level interoperability and the combination of open-source and IP-restricted blocks is achieved by adopting an AUTOSAR design philosophy. This means that there is a clear distinction between application software and basic software.

The application software is a set of high-level BMS routines (state estimation, safety routines, system diagnostics, etc.). Each of these routines has a fixed input and output data structure. These fixed input and output buses allow for the routine itself to be interchangeable and/or treated as a black box (in case of IP protected algorithms). Furthermore, any HW-dependent aspects such as communication, data storage and sensor treatment are delegated to the basic SW layer, making the application SW layer completely HW-independent. The routines of the application SW are coordinated by a master BMS.

The basic software is any software in charge of data storage management, the operating system, the communication protocols, input/output and bootloader. Those blocks are hardware dependent on the input side, but their output is clearly defined by input buses of the application SW. Hence to adapt the BMS to varying hardware components, only the application SW needs to change.

Since the BMS architecture consists of a cloud and an edge BMS that communicate with each other wirelessly, this also allows for interoperability after deployment. Just as algorithms can exchange data via clearly defined REST API endpoints, new application software or basic SW can be deployed

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via FW-over-the-air updates. This is achieved through a hardware-specific bootloader as part of the basic SW."

2.4 Software architecture Pillar 2

Figure 8 shows the software structure of the BMS for Pillar 2. The main BMS contains two microcontrollers, which are connected via serial bus to check the status of each. In case of an error, the still functional controller can initiate possible error corrections and prevent the system from serious damage. The main purpose of the Hercules TMS570 controller (MCU1) is to perform cell monitoring and the estimation of different SoX algorithms to ensure that the safety operating area (SOA) of the battery is always satisfied. The second controller (MCU2) handles the radio communication with all the MMS slaves. The radio communication on the MMS is handled within a bare metal application. To reduce power consumption the MMS controller is configured in sniff mode where the radio module and the main processor only periodically wake up. MCU2 which is located on the main BMS also serves as a backup controller in case MCU1 has a malfunction. The BMS applications will be executed on a real time operating system (FreeRTOS). The driver for the hardware abstraction layer (HAL) will partially be created with the help of the auto-code generation tool called HALCoGen. Different driver for e.g., CAN and UART will be written to communicate with the inverter and the cloud gateway.

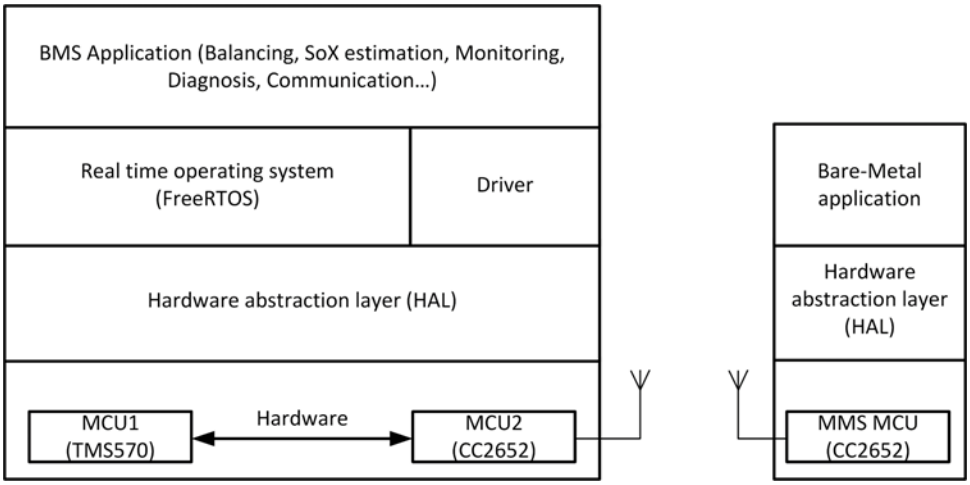

Figure 8: Software structure for the BMS (left) and MMS (right) in Pillar 2.

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3 WIRELESS BMS

In the current state of the art, wired BMS are used for battery-powered systems. These systems usually use Controller Area Network (CAN)-bus, I2C (Inter-Integrated Circuit) and SPI (Serial Peripheral Interface) communication [2]. To use these protocols a wire mesh is needed to collect various data and transmit it to the BMS master controller. Since each MMS can only handle the monitoring of a certain number of cells, multiple MMS are needed which subsequently also increases the amount of cabling. With the desire to obtain higher capacities in all types of battery powered applications, unavoidably more cells need to be installed in the battery pack leading to an increase in wiring.

To reduce cabling, costs and several other beneficial points latest research focused on wireless BMS communication. In the following, the main advantages and disadvantages of wired and wireless communication are discussed. The following paragraphs should not indicate a superior solution but rather give an idea about the general motivation why for certain use-cases, that are also part of the battery2life project, the wired or wireless approach is beneficial and worth researching.

Wired BMS

The basic architecture of a wired and wireless BMS is almost similar. The primary difference is that for the wired use case, the number of cables is increased. This especially increases the number of connecters which might be a possible source of failure due to a bad connection. Connectors take up to 8% of the electrical components in an electric vehicle propulsion system [3] and can be prone to failure especially in vibratory environments [4]. Additionally, in some cases, it can be difficult to identify the defect connector or wire which leads to an increase in reparation costs. Wired BMS have limitations in terms of assembly costs, scalability and the maximum area which can be covered [5]. On the other hand, wired communication has low latency, can transmit a high amount of data and has also a high reliability.

Wireless BMS

For the use case in the Battery2Life project where a wireless BMS master – MMS communication will be developed, the amount of cabling is slightly reduced compared to a wired BMS. Nevertheless, a reduction in materials and weight can be achieved by using this approach [6]. The main advantage which is also one of the goals of this project is, that a wireless communication between each of the modules (MMS) and the master BMS facilitates an easier disassembly and reassembly/reconfiguration process for a second-life battery pack. Depending on the specified use case (pillar 1 & pillar 2) a certain number of modules, where each of them communicates with the BMS master via wireless, can be reassembled more efficiently into a battery pack resulting in the specified energy/capacity. One of the downsides of a wireless BMS is a possible interference from other wireless networks which may cause connection interruption and transmission delay.

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It must also be ensured that the connection is encrypted and secured against remote attacks. In recent years, and by using state-of-the-art wireless communication technologies, as explained in the following paragraph, these issues are minimized.

Types of wireless communication technologies

Currently, there are various technologies available on how the communication of wireless BMS can be employed. Cao. Et al. classified these technologies based on their communication range [4] which can be seen in Figure 9: Classification of wireless communication technologies applied in wireless BMS [4]. They differentiate between short-range, Wireless Lan (WLAN), Metroplitan Area Network (MAN), and Wide Area Network (WAN). These existing technologies have all been part of recent literature of wireless BMS. The most relevant technologies for the BMS master – MMS communication especially for the battery2life project can be considered as short-range communication technologies, therefore a short overview of these technologies is given in the next paragraphs.

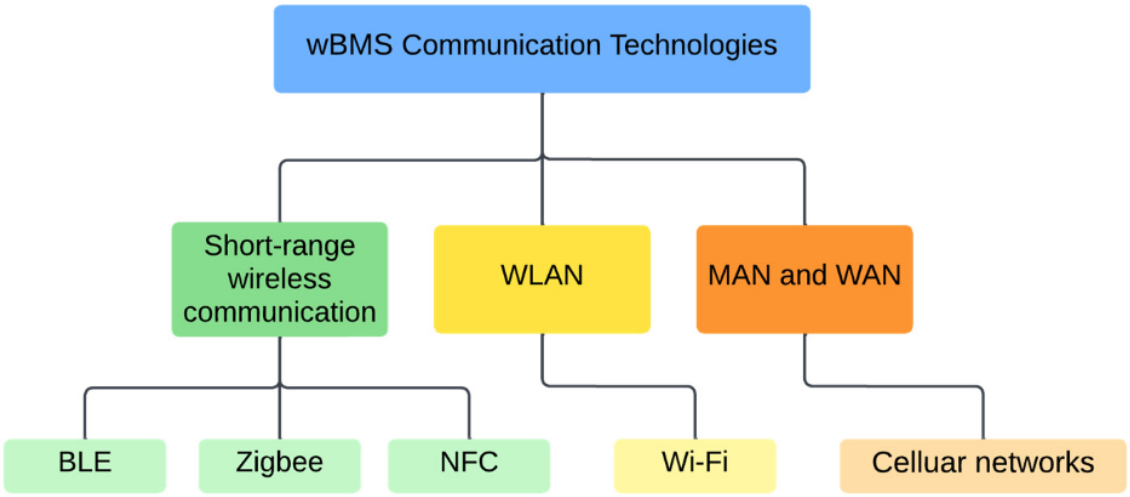

Figure 9: Classification of wireless communication technologies applied in wireless BMS [4].

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- **Bluetooth Low Energy (BLE)**

This technology operates in the 2.4GHz band and is mostly used in smartphones but recently gaining interest in the automotive area. The main reasons are its low energy consumption and widespread diffusion [7]. Some of the disadvantages of this technology are that it might be problematic to ensure high speeds and sufficient transfer rate of high amounts of data. Also, the sensitivity to channel noise could be a problem for the necessary safety standards in the automotive industry [8]. Two main operational modes are possible using a device as a peripheral or as a central, making it especially attractive for the MMS – BMS master communication.

- **Zigbee**

Zigbee is a wireless communication system designed for low-power, short-range, and low-data rate transmissions. It is built on the IEEE 802.15.4 standard and aims to provide dependable, cost-efficient, and energy-saving wireless communication across short distances. For each device different roles can be assigned, making it possible to use it as a router, coordinator, or end device. Each of these roles has different functionalities, like establishing a network, forwarding data and establishing an indirect connection. Additionally, it enables to send messages through intermediate nodes if direct communication is not feasible. This technology is also working in the 2.4GHz frequency band. Besides its strengths of energy efficiency, cost-effectiveness, easy scalability, and good mesh networking the main disadvantages are similar to BLE, the low data transfer capacity [4].

- **Near field communication (NFC)**

NFC is one of the three main short-range technologies that uses magnetic fields instead of electric fields for data transmission. One necessity for this technology is, that the devices need to be in close proximity to each other (couple of centimetres). The main advantages are its low energy consumption due that the activation of one of the devices only happens if, it is near another NFC device. Additionally, it can be considered secure because it only enables short-range communication, which is difficult to exploit from further away than a couple of centimetres [9].

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3.1 Pillar 1

Wireless Communication Between BMS Master and MMS (Master-Slave Communication)

In the modular architecture of battery management systems, the wireless communication between the **BMS Master** and the **MMS (Module Management System) units** is a critical aspect of the Master-Slave concept. This communication is handled by STM32 microcontrollers embedded in both the BMS Master and the MMS units, facilitating real-time data exchange within the system.

The STM32 microcontrollers in the MMS units are responsible for monitoring specific groups of cells within the battery pack. They gather essential parameters, such as voltage, temperature, and current, and communicate this data wirelessly to the BMS Master, which is also controlled by an STM32 microcontroller. This architecture ensures streamlined communication for system-wide management.

The wireless link between the BMS Master and MMS units allows for efficient system monitoring and control, including:

- **Data Transfer**: STM32 microcontrollers in the MMS units continuously transmit key parameters like voltage, temperature, and current from individual cells to the BMS Master. This data is crucial for maintaining balanced charge/discharge cycles, monitoring cell conditions, and detecting potential faults within the system.
- **Diagnostics and Control**: The BMS Master, using its STM32 microcontroller, processes the data received from the MMS units and makes real-time decisions, such as activating cell balancing, detecting faults, and controlling the charging and discharging processes. This ensures uniform performance and safety across all battery modules.
- **Fault Management**: In the event of anomalies, such as overvoltage, overheating, or imbalances in the modules, the wireless communication between the BMS Master and the MMS units—both equipped with STM32 microcontrollers—enables quick identification and response to these issues, ensuring operational safety.

This wireless communication setup, supported by STM32 microcontrollers, allows the system to scale easily. Additional MMS units can be integrated without the complexity of physical wiring, making this approach particularly useful in large battery systems such as those used in electric vehicles or industrial energy storage.

By integrating STM32 microcontrollers into the BMS Master and MMS units, the system achieves real-time, wireless, master-slave communication, enhancing both the efficiency and scalability of the battery management system.

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Wireless Cloud Communication Between BMS Master and External Systems (Cloud Communication)

In addition to the internal communication between the BMS Master and MMS units, the BMS Master also supports **wireless cloud communication** with external systems, such as PCs, cloud platforms, or other remote monitoring systems. This cloud communication serves a different purpose and is focused on remote monitoring, data analysis, and system updates.

The wireless communication framework between the BMS Master and MMS units, powered by STM32 microcontrollers, represents a robust and scalable solution for battery management systems. This Master-Slave architecture ensures seamless data transfer and real-time control across the battery modules, enabling precise monitoring of key parameters such as voltage, temperature, and current.

By eliminating the need for complex wiring, this wireless setup enhances the system's flexibility, allowing for easy expansion as more modules are integrated. The real-time diagnostics and fault management capabilities, made possible by the reliable communication between the BMS Master and MMS units, improve the system's overall safety, efficiency, and performance.

This approach is particularly advantageous for large-scale applications, such as electric vehicles and industrial energy storage, where scalability and operational safety are critical. In conclusion, the use of STM32 microcontrollers within the wireless communication architecture ensures that the BMS system can adapt to evolving needs while maintaining a high standard of reliability and control.

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3.2 Pillar 2

For Pillar 2 (the Domestic storage use-case) the 1st life MMS will be replaced by an MMS with a wireless 2.4 GHz radio frequency (RF) communication interface. Such a wireless communication interface has advantages for the user and the supplier:

- Reduced costs due to missing module isolation components and connectors.
- Reduced re-assembling and manufacturing complexity (transition process from first to second-life).

However, there are also a lot of challenges to overcome when using an RF communication:

- Interference due to the housing of the pack or module.
- Security: Communication lines should be secured.
- Power consumption: As low as possible since the MMS will be powered by the battery module itself.

The RF communication is implemented with the help of a wireless microcontroller (MCU) CC2652 from Texas Instruments. This wireless MCU includes a dedicated RF-core which handles the radio protocol. Such MCUs offer a low power consumption and are therefore suitable for battery powered applications. For the 2.4 GHz communication a printed-circuit board (PCB) inverted-F antenna was designed to keep the PCB dimensions compact. With the chosen frequency also a Bluetooth mesh could be realised. However, for this project a custom communication protocol was developed to have full access to all parameters. Each wireless message is encrypted by using the 128-bit Advanced Encryption Standard (AES). To detect faulty messages a cyclic redundancy check (CRC) checksum was added to each message. In case of a faulty message the message will be re-transmitted.

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4 EMBEDDED-EIS CONFIGURATION ON ADVANCED BMS SLAVES

4.1 Pillar 1

For pillar 1 the slave boards will be including cell level Electrochemical Impedance Spectroscopy (EIS) measurements. The EIS will be used for State of Charge (SOC) and State of Temperature (SOT) estimation. EIS relies on exciting the cell at various frequencies and analysing the cell reaction. This non-invasive technique allows to obtain insight about the various layers that compose the cell. These layers provide direct insight about various SOX [Pietro Iurilli, Nelson Koch, Rafael E. Carrillo, Claudio Brivio, DRT-based SoC estimation for commercial Li-ion battery pack, ICCEP 2023]. For instance tracking the evolution of the layers over time provides details about SoH. Whereas absolute values of layers (i.e. peaks) provide information about SoC. For cost efficiency, we are currently investigating the best option for EIS at module level. There are two main possibilities:

A) Using a single EIS (generation and sensing) for a module and multiplex it over the different cells.
B) Using a single EIS generation at module level and sensing at each cell level.

For SOC the EIS will be carried out on a regular basis (after several days or weeks, when some degradation has occurred). The EIS data will be processed in order to extract cell parameters that will be used in the Equivalent Circuit Model (ECM) that is then used to compute the SOC in “real time”. The ECM relies on standard sensors (current/voltage) to carry out the SOC estimation. Only the ECM model parameter estimation requires the EIS.

For SOT estimation, EIS is carried out more often. The time interval between two EIS measurements will be determined by the system requirements. The EIS measurement is then translated into a cell core temperature.

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5 CLOUD COMMUNICATION

The cloud communication architecture is designed to support the BMS in enabling real-time monitoring, control, and management of 2nd-life BS. The main goal is to ensure that the BMS and cloud can communicate wirelessly, safely, and efficiently.

5.1 Purpose and Role

The cloud platform will centralize the data from distributed BMS units, allowing advanced algorithms for State of Charge (SoC), State of Health (SoH), State of Safety (SoS), and State of Warranty (SoW) to be run in the cloud for improved battery management. ICCS will oversee the development of an open architecture that ensures transparent data exchanges with third-party systems, thus enabling interoperability across multiple applications.

5.2 Cloud Platform Structure and BMS-Cloud Communication

- **Architecture**: The cloud platform will be designed to handle data input/output from the BMS, enabling real-time processing and visualization. This architecture will include:
    - **Data Collection Layer**: Responsible for collecting sensor data from the BMS.
    - **Data Processing Layer**: Processes, analyzes, and applies machine learning models (where applicable) to forecast battery performance (e.g., SoX algorithms like SoC, SoH) will be held in third parties cloud services.
    - **User Interface Layer**: Provides a web-based or mobile application interface for real-time battery monitoring and management.
- **Wireless BMS-to-Cloud Communication**: ICCS will define specific protocols for wireless communication between the BMS and the cloud, ensuring compatibility with existing and emerging technologies (such as LoRa, 5G, or Wi-Fi).

5.3 Data Communication and Interoperability

Interoperability is essential for the cloud platforms to ensure seamless compatibility with external systems and third-party platforms, and which can be achieved by using standardized communication protocols. Wireless communication increases deployment flexibility, especially in remote or decentralized battery systems.

Simultaneously, conventional wired solutions will be examined for specific applications that need lower latency or higher reliability. Both communication methods will be integrated into a modular architecture, supporting open-source and IP-restricted components as outlined in Deliverable D1.3 “BMS Specifications and Advanced Algorithms for 2nd Life”.

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5.4 Security and Scalability

Security is paramount in cloud communication, particularly in scenarios involving wireless data transmission. To safeguard against data tampering and interception, authentication layers will be incorporated.

The cloud platform will be designed to be scalable and able to accommodate the expanding quantity of data points and battery systems. Whether supporting small-scale home energy storage or large-scale industrial applications, it will provide reliable and scalable data processing to meet the diverse needs of second-life battery solutions.

5.5 Future-Proofing and Flexibility

The cloud platform is designed to be future-proof and versatile, ready to accommodate upcoming communication technologies like 5G and Artificial Intelligence (AI) powered predictive maintenance, along with other future BMS advancements. Its open architecture allows for seamless integration with third-party cloud services and external battery monitoring systems, ensuring long-term flexibility to adapt to new battery technologies and evolving market needs.

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6 CONCLUSION

One of the main goals of the Battery2Life project is to enable a smooth transition of battery systems to their second-life. With this deliverable the groundwork for the two pillar specific battery systems is defined and the results will be further developed with the following tasks and work packages of this project. In the next paragraphs the essential conclusions of the main chapters are given.

The hardware topology in Pillar 1 is designed around a master-slave architecture, where the BMS Master coordinates the entire system, delegating local control and monitoring to BMS slaves. After evaluating various communication methods, it is decided to prioritize wireless as the exclusive communication method for the BMS slaves. This decision ensures maximum flexibility, simplifies system installation, and enhances remote monitoring capabilities, especially in larger or distributed battery systems. CSEM commit for providing wireless BMS Slave units, ensuring seamless integration and optimal performance across the entire system. Also in Pillar 2, a wireless master-slave architecture will be used to capitalize on the previously mentioned benefits. The information exchange between the BMS master and the inverter of the photovoltaic panels is realised by using RS-485 that the discharging and charging behaviour can be adjusted based on this data. Additionally, active balancing is realised in Pillar 2. The balancing chip ETA3000 was chosen due to its ease of use, the small footprint, the low price, and its safety features. Two cells per chip can be balanced with an accuracy of up to +-30mV. Another advantage of this chip, discussed in depth in Chapter 2.2, is its integrated safety mechanisms and low power consumption.

In chapter 3 the advantages and the disadvantages of wireless communication and details about different technologies is given. For Pillar 1 the communication between the BMS Master and the MMS will be handled by STM32 microcontrollers that are embedded in both units. For the domestic storage use case in Pillar 2 the communication will be realised with the microcontroller CC2652 from Texas Instruments. This controller enables low power consumption, which is critical for battery-powered applications. Additionally, a printed circuit board inverted-F antenna was designed to keep the PCB dimensions compact, enabling the 2.4Ghz communication. To ensure a safe and reliable communication the 128-bit Advanced Encryption Standard (AES) is used, and a cycling redundancy check is implemented.

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The EIS measurements are implemented in Pilar 1 and currently two different approaches are investigated. One option is to use a single EIS (generating/sensing) and multiplexing it over different cells. The other option is to use a single EIS at module level and sensing at each cell level. For both options the measurement will be carried out on a regular basis to determine the SOC. For the internal cell temperature determination, which is also done via EIS, the time interval is reduced.

The cloud communication architecture defined by ICCS plays a crucial role in enabling the next-generation BMS for 2nd-life battery applications, supporting real-time monitoring, active balancing, and advanced SoX. Wireless data transfer will be preferred as it gives more deployment flexibility, although wired solutions will be explored as they provide reliability for specific use cases. The architecture's modular and interoperable design enables effortless integration with third-party platforms, providing scalability and long-term adaptability. Security remains a priority, with encrypted data transmission safeguarding sensitive battery information. The initial definitions of the cloud communication were introduced in D1.2 “Open-source and interoperable BMS principles” and D1.3 “BMS Specifications and Advanced Algorithms for 2nd Life”, providing the foundational elements, while more detailed specifications and implementations will be available in Deliverable D2.3 “BMS open cloud platform”, which will be submitted in month 12. ICCS’s cloud communication framework is built with a future-ready approach, designed to adapt to emerging technologies like AI-powered maintenance and 5G, while effectively addressing the varied needs of the second-life battery market.

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