NEXT GENERATION OF MULTIFUNCTIONAL, MODULAR AND SCALABLE SOLID STATE BATTERIES SYSTEM

D1.3 Report on the final interfaces

EXTENDED project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101102278.

Document details	
Project Information	
Project Acronym/ Name:	EXTENDED
Project URL:	https://extendedproject.eu/
Project Type:	Research and Innovation Action (RIA)
EU CALL:	HORIZON-CL5-2022-D2-01-05 Next-generation technologies for High-performance and safe-by-design battery systems for transport and mobile applications (Batteries Partnership)
Grant Agreement No.:	101102278
Project Start Date:	01/06/2023
Project End Date:	31/05/2026
Document details	
Work package:	WP1
Deliverable:	D1.3 Report on the final interfaces
Due date of Deliverable:	31/05/2024
Actual Submission Date:	31/05/2024
Name of Lead Beneficiary for this deliverable:	Report Author(s): Mohammad Hossein Morshed Varzandeh (ABEE)
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Revision:	1.0
Dissemination Level:	PU - Public

Document History			
Version	**Date**	**Comment**	**Modifications made by**
0.1	03/05/2024	Draft document of chapter 4	Jon Gastelurrutia (IKL)
0.2	23/05/2024	Section 4.1	Jagadish Babu Vemula (ABEE)
1.0	30/05/2024	Review	Matthias Hessmann (FHG)
1.0	30/05/2024	Review	Basit Jimoh (THI)

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Glossary and Abbreviations	
LIB	Lithium Ion Battery
SSB	Solid State Battery
BMS	Battery Management System
TMS	Thermal Management System
R0	Internal Ohmic Resistance
VLE	Vapor Liquid Equilibrium
TIM	Thermal Interface Material
PTC	Positive Temperature Coefficient
NTC	Negative Temperature Coefficient
HV	High Voltage
LV	Low Voltage
BJB	Battery Junction Box
BTMS	Battery Thermal Management System
SOH	State of Health
SOC	State of Charge
WG	Water-Glycol

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Executive Summary

This deliverable outlines the final design and interfaces for a multifunctional, modular, and scalable solid-state battery (SSB) system. The focus is on achieving a cohesive integration of mechanical, electrical, and thermal components to ensure the system meets high standards of performance, safety, and efficiency. By addressing these key areas, the deliverable provides a comprehensive blueprint for developing SSB systems suitable for transport and mobile applications, highlighting the necessary design principles and innovative solutions.

Key aspects covered include:

- Mechanical Design
- Electrical Architecture
- Thermal Management

The report concludes with a summary of the innovative approaches and key findings, emphasizing the integrated design of mechanical, electrical, and thermal elements to develop safe, efficient, and scalable SSB systems. This work lays a foundation for future advancements and broader implementation of solid-state battery technology.

1. Introduction

This report focuses on the development and definition of the final interfaces for a multifunctional, modular, and scalable solid-state battery (SSB) system designed for transport and mobile storage applications.

A battery pack is a complex mechatronic system that integrates multiple technologies, each with specific requirements and constraints. For instance, the optimal thermal solution may not be entirely compatible with the lightest cell compression system, or the best thermal sensing solution might be unimplementable due to Battery Management System (BMS) restrictions. This report defines system-level requirements and proposes high-level conceptual design solutions to meet these requirements. Furthermore, it delineates the interactions and interfaces between mechanical, thermal, and electrical proposals.

The document analyses different applications to define some basic requirements:

- Mechanical Requirements: Ensure structural integrity and the ability to withstand mechanical stresses and strains during operation under various environmental conditions.

- Electrical Requirements: Provide efficient energy distribution and safe management of the cells' charge and discharge.

- Thermal Requirements: Maintain optimal operating temperature with the lowest possible thermal dispersion, which is crucial for battery longevity. This includes controlling the ambient temperature within a range of -10 ºC to 45 ºC and managing the cells' minimum and maximum temperatures.

The mechanical, electrical, and thermal architecture is developed in the following chapters, offering a comprehensive overview of how these interfaces and components interact to create a safe, efficient, and high-performance battery system. Throughout the report, diagrams and schematics illustrate the arrangement of key components and the integration of the proposed solutions into the overall system. This document does not go in depth into each of the categories but tries to give an overview of the boundary conditions in each part.

2. Mechanical boundary diagram

The mechanical boundary diagram outlines the structural and functional relationships between the various components of the solid-state battery (SSB) system. This section provides an overview of the key mechanical elements that ensure the battery pack's integrity, safety, and performance.

2.1. Mechanical architecture

The mechanical architecture of the solid-state battery (SSB) system is a critical aspect of its overall design, ensuring not only the structural integrity and safety of the battery pack but also optimizing its performance and durability. This section delves into the various components and design principles that underpin the mechanical layout of the battery system, which is essential for its effective integration into electric vehicles.

The Figure 1 provides a detailed schematic of the high-level mechanical architecture of the battery module. All these elements will be further developed in deliverable 2.1 with the conceptual design and further detailed during the development of the project. The illustration highlights the following key components and their roles within the battery pack:

Mechanical Housing: The external casing that encloses and protects the battery cells from physical damage and environmental exposure. It is designed to be robust yet lightweight, using materials that offer high strength-to-weight ratios.

Battery Cells Arrangement: The internal configuration of the battery cells is optimized for space efficiency and thermal management. Cells are arranged to minimize the distance between them, enhancing the structural cohesion and facilitating uniform temperature distribution.

Bus Bars: These are conductive bars that connect the battery cells, enabling efficient power distribution within the pack. The use of solid aluminium or insulated tin-coated copper bus bars ensures low resistance and high conductivity, crucial for high-performance applications.

Pressure Control Mechanisms: Integrated systems that maintain the appropriate pressure within the battery pack to ensure cell stability and performance. This includes features to manage the compression of cells, which is vital for the optimal operation of solid-state batteries.

Venting Solutions: Essential for managing internal pressures and preventing the buildup of gases that could lead to hazardous conditions. The dual-stage venting system combines passive venting for regular pressure adjustments and active venting for emergency scenarios.

Thermal Pathways: Design elements that facilitate efficient heat transfer away from the cells to maintain their temperature within the desired range. This includes cooling plates and thermal interface materials that connect to the thermal management system (TMS).

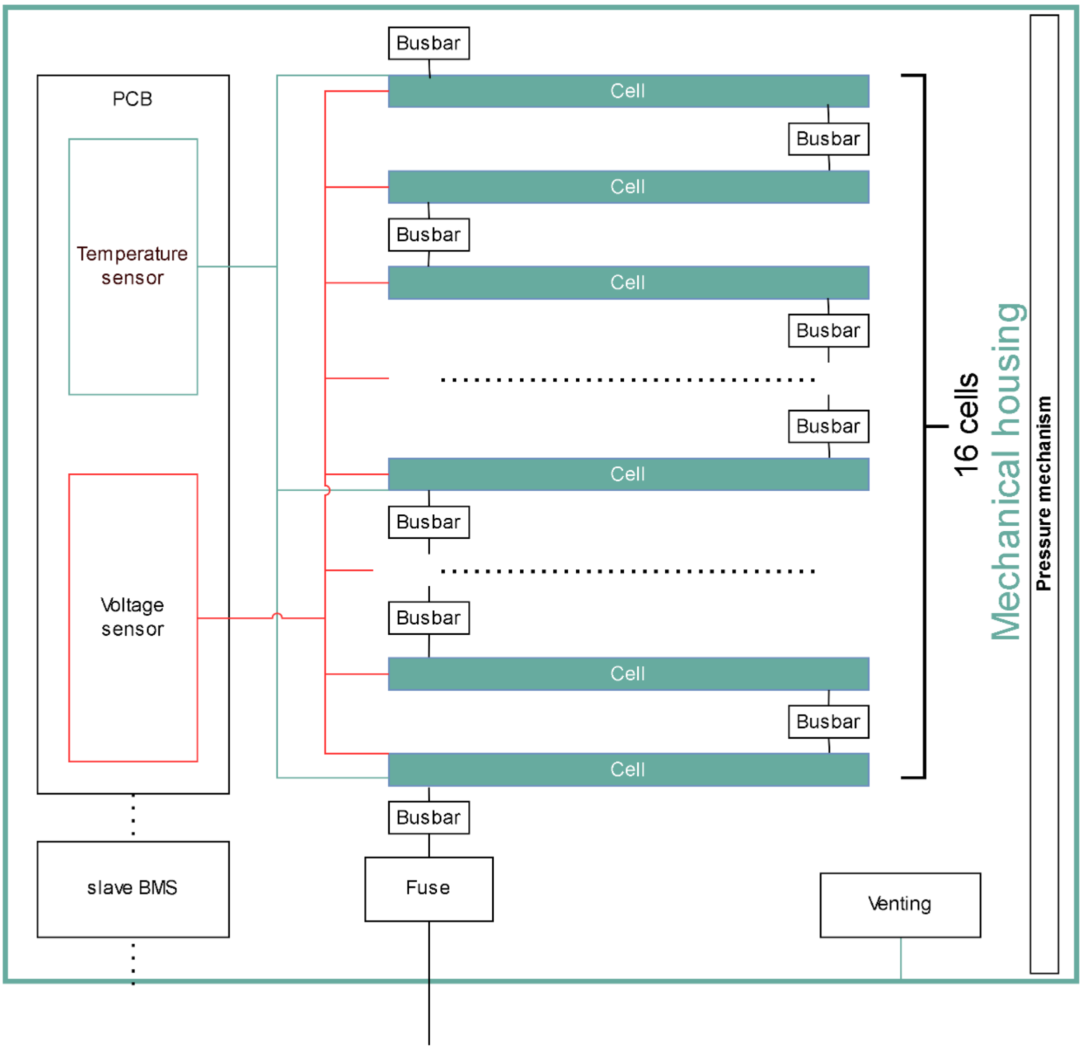

Figure 1. High-level mechanical architecture

3. Electrical boundary diagram

This chapter gives an overview on the electrical system in between the high voltage (HV) battery and the internal and external electrical subsystems. Generally, each use case inside the EXTENDED project uses the HV battery as a central energy storage system. To provide and distribute power to all subsystems, each use case needs multiple electrical interfaces. In this chapter, these interfaces and functions will be described based on the general high-level electrical system architecture.

3.1. Electrical architecture

Figure 2 shows the high-level architecture of the electrical system, that can be applied to each of the use cases defined in deliverable D1.2. The electrical system, especially for mobility use cases, contains several different voltage levels such as the HV battery system, low voltage (LV) board net, AC load as well as a DC and AC charger. Typical HV battery system voltages are thereby between 400 VDC and 800 VDC.

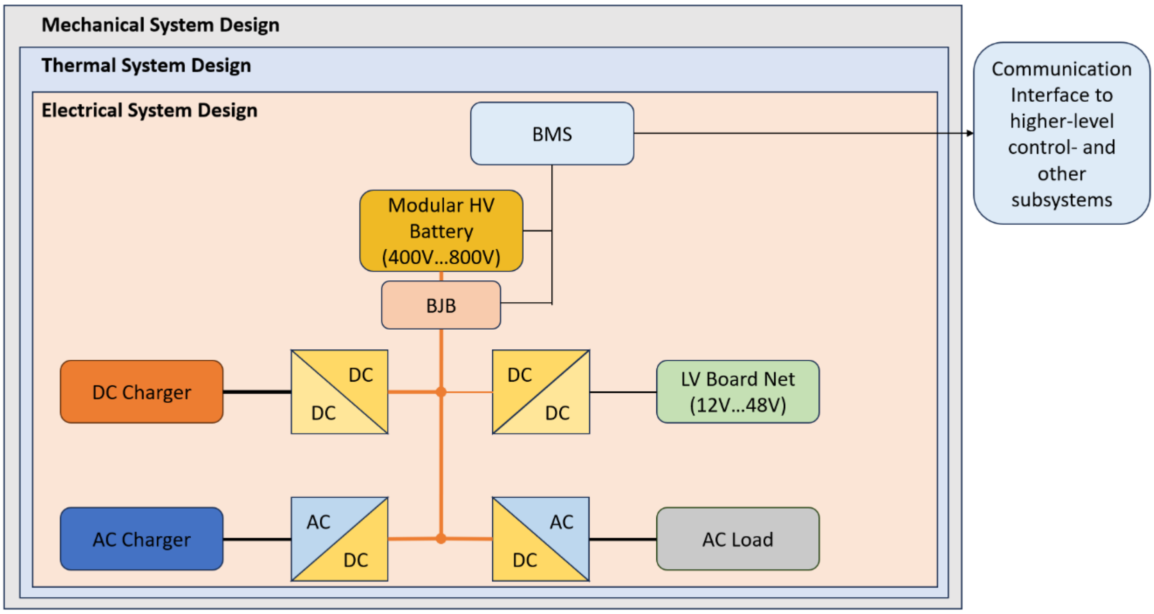

Figure 2 High-level electrical architecture

The HV battery is monitored by the BMS, which provides a communication interface to higher level control and management systems, such as the thermal system or the central control unit. Typically, the communication between the BMS and other control units is established via a CAN or Ethernet interface. Table 1. Interface Messages between BMS and higher-level Control Unit and other Subsystems summarizes key BMS messages and their relevance for higher-level system control systems and other subsystems. A more detailed BMS architecture, including the internal wireless BMS communication interfaces developed by LUM, CEA and FHG, will be described within deliverable D3.1. The deliverable D3.1 furthermore describes the functionality of the advanced sensors, developed by LUM and the single cell electronics developed by FHG.

Messages	*Relevant for*
Physical parameters	
Cell voltage	Energy management, central control unit, external charger, drive train control, data logging
Cell temperature	Thermal management, central control unit, external charger, drive train control, data logging
Cell impedance	Energy management, central control unit, thermal management, data logging
Pack current	Energy management, central control unit, external charger, drive train control, data logging
State estimators	
SOH	Energy management, central control unit, data logging
SOC	Energy management, central control unit, drive train control, external charger
SOF	Energy management, central control unit, drive train control, external charger
Flags	
Flag cell voltage	Thermal management, central control unit, external charger, drive train control, data logging
Flag cell temperature	Thermal management, central control unit, external charger, drive train control, data logging
Flag pack current	Thermal management, central control unit, external charger, drive train control, data logging

Table 1. Interface Messages between BMS and higher-level Control Unit and other Subsystems

As the battery forms the central energy storage of the system, the remaining electrical subsystems must be connected to the HV battery via safety-critical interfaces such as the Battery Junction Box (BJB) and the AC-DC as well as DC-DC converters. Within the HV system, the BJB acts as the central interface to the system's HV battery. The BJB is thereby controlled and monitored by the BMS and allows safe battery operation within the safe operation area. A more detailed description of the BJB architecture is given in deliverable D2.1.

For recharging the HV battery, additional interfaces to an external energy source are needed. Especially in mobility applications, different charging strategies are used to provide maximum flexibility, regardless of the available infrastructure. However, not only the voltage levels between the charger and the HV battery, but also the charging profiles can differ in order to prolong the lifetime and minimize the charging time of the HV battery. For this reason, the HV battery interfaces via a DC-DC converter to the external DC charger. The DC-DC converter is thereby used to adjust the current and voltage profile while charging, based on the specifications of the HV battery. In addition to DC charging, the battery can also be charged by using an AC charger, such as a 11 kW wallbox for automotive applications. The HV battery must therefore be connected to the AC charger via an AC-DC converter, which converts the AC signal from the power grid to a DC-based charge profile.

Another part of the electrical system design consists of the electrical load and the LV board net. Depending on the application, both subsystems can be powered by the HV battery. To reduce the HV voltage to the voltage of the LV board network, an additional DC-DC converter is required as an interface to the HV system. The power path to the AC load, such as the electric motor of a vehicle is made via another AC-DC converter. This allows to provide the desired frequency and voltage level to the AC load, depending on the application and load case.

However, it cannot be neglected that the electrical subsystems and interfaces described must be mechanically and thermally integrated into the overall system design. This integration depends on the system requirements and must be evaluated individually for each application. Therefore, not only the integration density but also the thermal connection to the cooling elements must be considered in order to build lightweight, high-performance and low-maintenance battery systems.

In residential applications, a battery storage system offers numerous benefits, acting as a versatile solution for optimizing energy usage, enhancing efficiency, and providing resilience. Here are the main use cases for residential batteries:

1. **Energy storage.** Homeowners can capture excess energy generated by renewable sources like solar panels during period of abundant sunlight,

storing it for later use when energy demand is higher or solar production is limited.

2. **Peak shaving.** Deployment of stored energy during peak demand periods to reduce reliance on the grid and mitigate high electricity costs.
3. **Arbitrage.** Storing energy when rates are low and discharging it when prices are high, thereby maximizing cost savings.
4. **Backup.** Batteries can provide essential backup power during grid outages or emergencies, ensuring uninterrupted operation of critical appliances and maintaining household comfort and safety.

Figure 3 shows an electrical diagram of a residential application battery system with a capacity of 5 kWh.

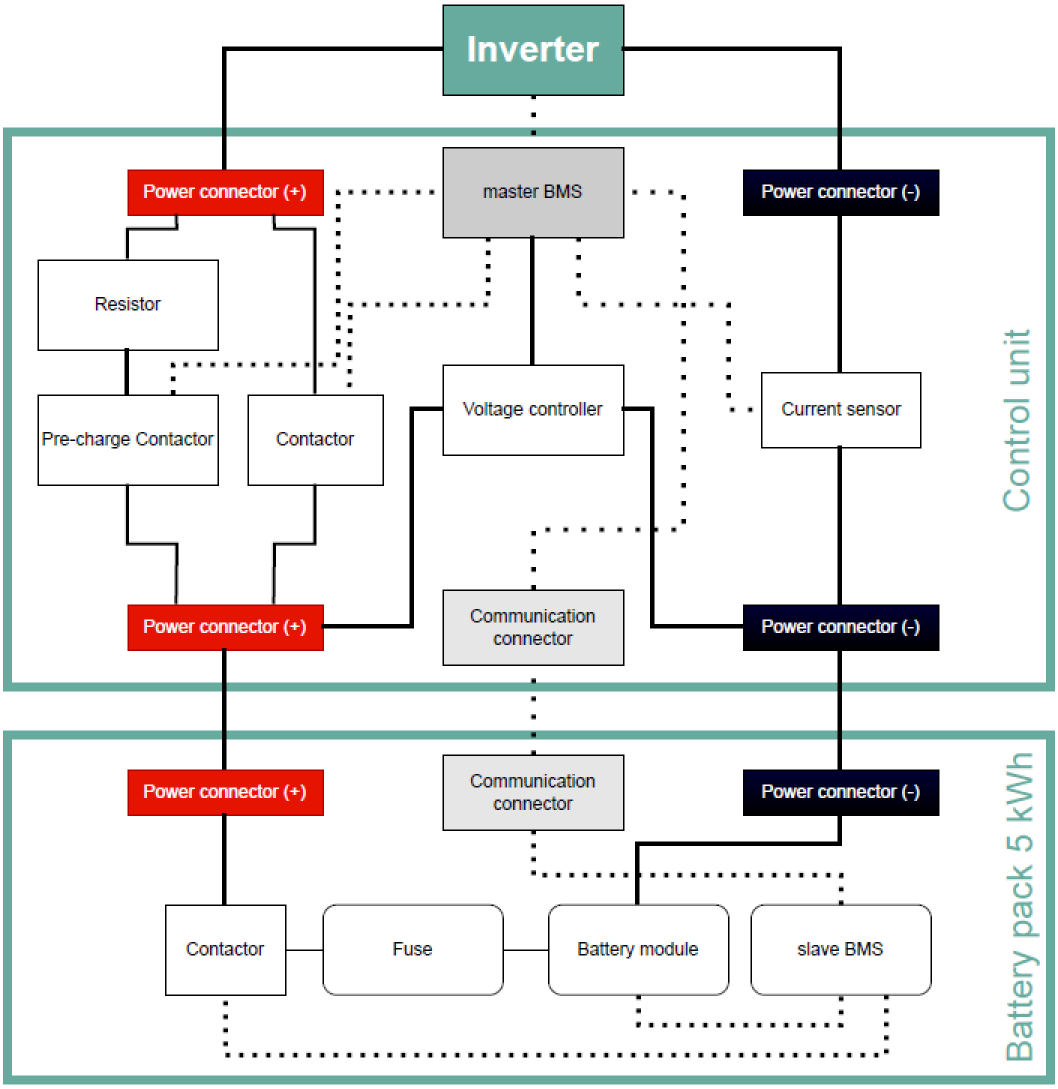

Figure 3. Boundary diagram of a 5 kWh capacity residential application system

4. Thermal boundary diagram

The thermal management system of a battery pack (TMS) is responsible of maintaining a good operative temperature with the lowest possible thermal dispersion at pack level. It is known that this thermal performance has a high impact in the life expectancy of the battery pack [1] . This should be done with the best possible efficiency independently of the ambient temperature and electrical solicitations of each application. For the solid-state cell (SSB) of EXTENDED this could require providing both cooling and heating. The purpose of this chapter is to define the general thermal architecture of the TMS and its boundaries with mechanical and electrical architectures.

4.1. Thermal boundary diagram:

Figure 4 and Figure 5 illustrate the thermal boundary diagram of the module, encompassing the entire battery thermal management system (BTMS), the module itself, and the control unit with essential components like sensors and power supply for control purposes. The entire battery setup is positioned between two primary cooling plates located on each side, securely fixed to maintain the stability of the battery pack. This arrangement is housed within a module casing that includes pressure plates and terminals for electrical connections.

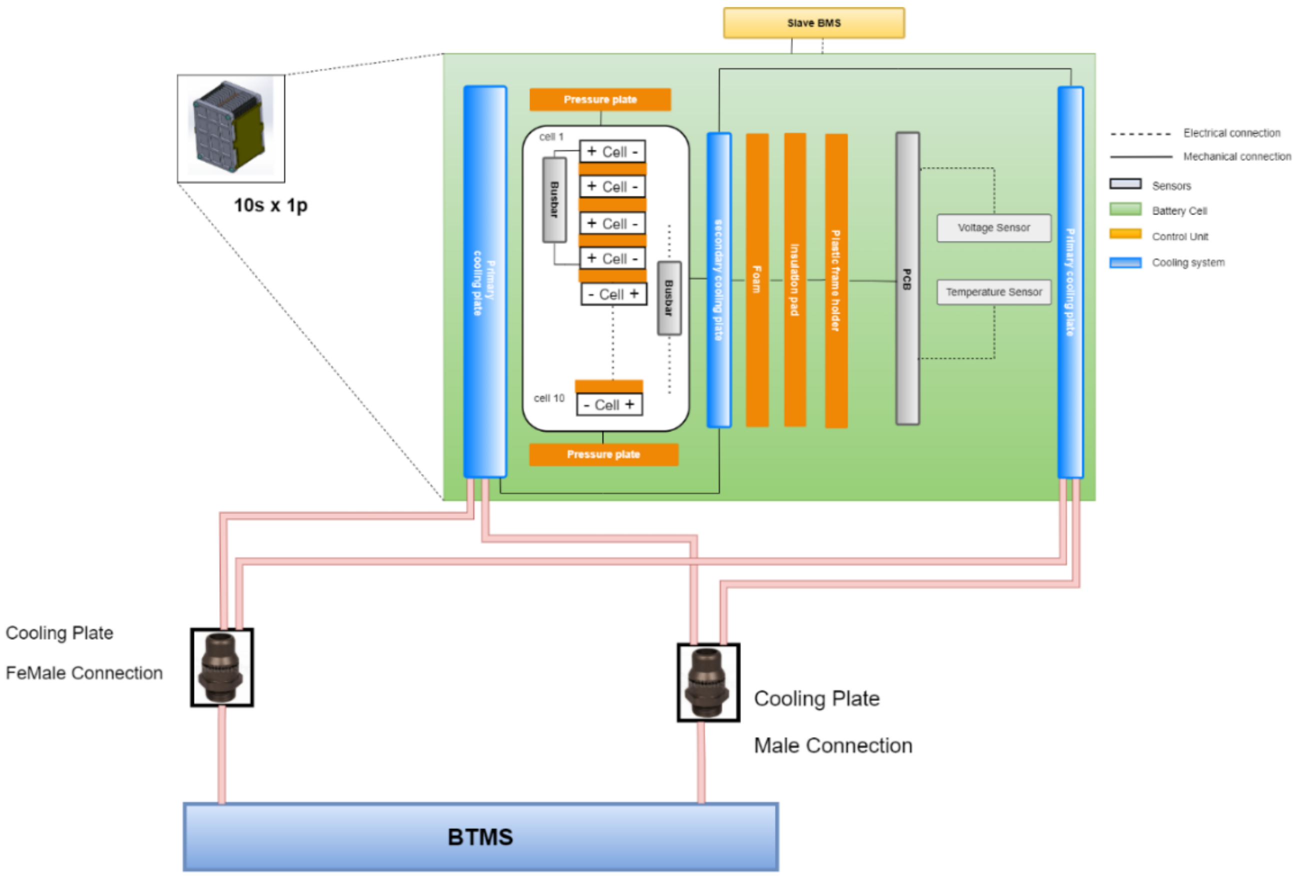

Figure 4. Schematic of the battery module with various components and BTMS arrangement.

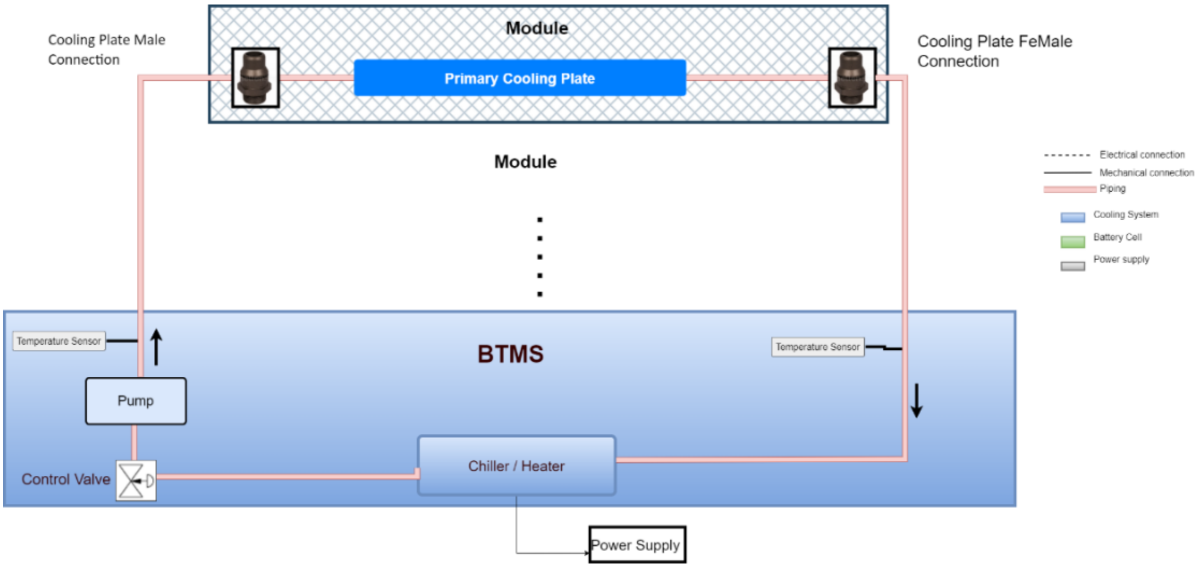

Figure 5. Schematic of the battery thermal management system for the battery module.

The cooling plates are linked to the BTMS, which includes a chiller/heater through control valves and a pump, while the module controller is connected to the control unit. In Figure 4 and Figure 5, dashed lines represent electrical connections, and solid lines represent mechanical connections.

The flow rate within a module can be adjusted via a flow control valve operated by the control unit. A temperature sensor at the module level measures both ambient and coolant temperatures. The module's cooling circuit connects to the cooling interface to ensure an adequate coolant flow rate and temperature, thereby maintaining the battery's temperature within the desired range.

4.2. Thermal architecture

Figure 6 shows the high-level thermal architecture to be deployed in D2.1 and evaluated using numerical simulation tools in D4.2. Depending on its final complexity, the TMS can be composed of five basic elements: the battery pack itself (thermal source), the internal cooling/heating group (1st loop), the external cooling/heating group (2nd loop), the environment at ambient temperature (thermal sink) and the battery management electronics or BMS (sensing/control).

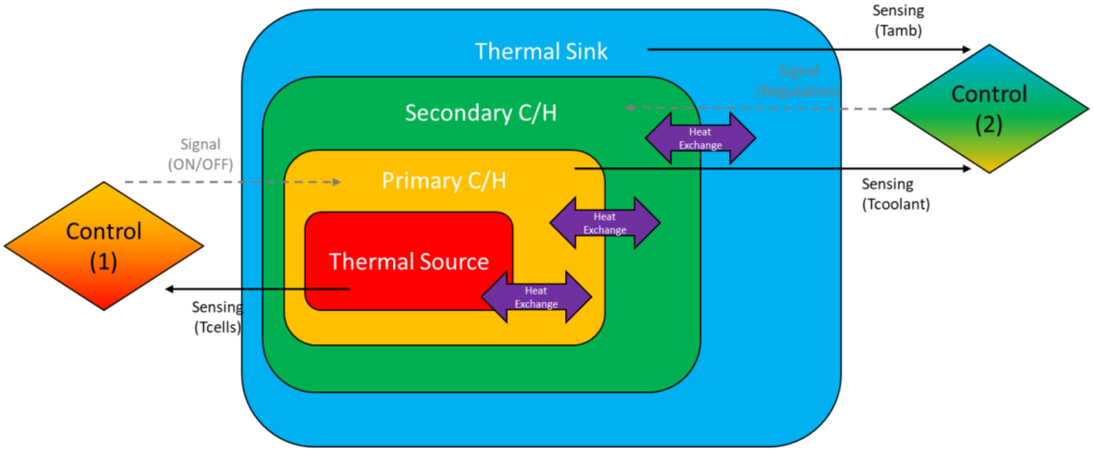

Figure 6. High- level thermal architecture.

In this particular case the battery pack will be composed of an array of pouch type SSB. This technology normally withstands higher temperature and pressure levels than standard lithium ion batteries (LIB)[2]. The energy conversion that occurs in the battery pack during charge or discharge is not ideal and always generates a heat release. This heat amount depends mainly on the internal or ohmic resistance (R0) that shows the battery system and the current level that is circulating through it. The internal resistance of a SSB depends mainly on its state of health (SOH), state of charge (SOC) and its absolute temperature (T) [3]

It is well known that LIB cells shows a quite poor thermal conductivity and a big thermal inertia. Due to this, the heat diffusivity in the body of any cell is quite poor and it is quite difficult to extract the heat from them [4]. The problem in SSB cells can be assumed similar, so it is mandatory to improve the so called "thermal path" using well designed cell holders and module level structures.

More details about the thermal characterization are given in deliverable D4.1. A more detailed description of the components and the constructive solution used to create such "thermal paths" can be found in deliverables D5.1 and D2.1 .

4.3. Cooling

As it has been pointed out in the previous chapter the SSB array will generate some heat power when is operating and, depending on the mechanical structure, it can be quite difficult to dissipate this heat to the ambient. This is done using the primary or internal cooling loop close to the battery pack (blue line in Figure 7 [5]). If the goal is to operate at temperatures below the ambient temperature a secondary or external cooling loop is needed (green line in **Error! Reference source not found.**). This TMS can be quite sophisticated in the case of an electric vehicle, but the idea is to obtain the best possible efficiency in order not to drain to much energy from the battery pack. In the framework of this project, the design of this secondary loop is out of the scope.

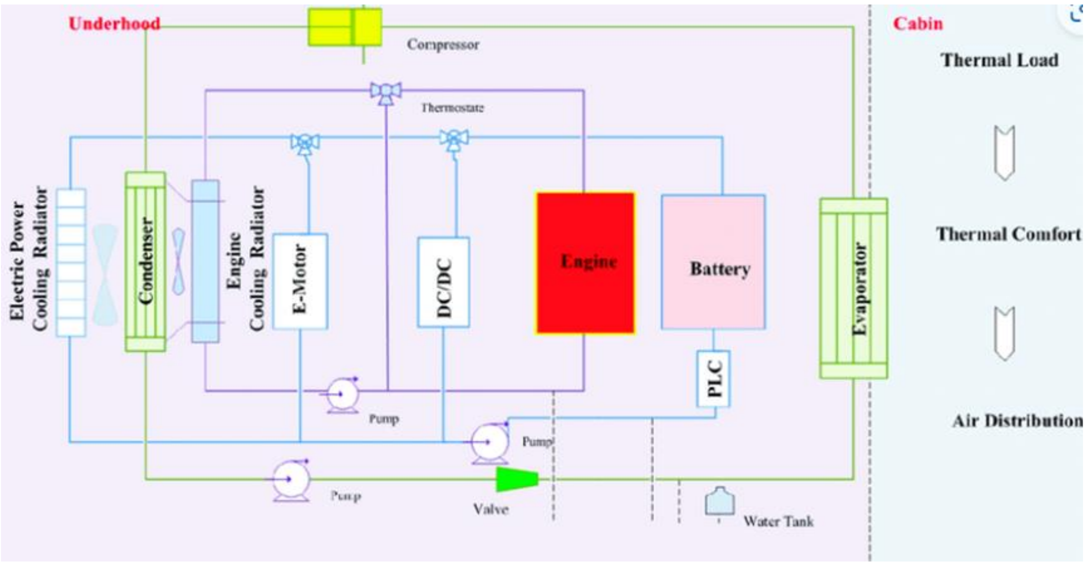

Figure 7 : Example of a typical TMS for a light EV

Primary cooling loop is composed of a heat exchanger in direct thermal contact with the battery itself. If the heat release from the battery array is low enough this cooling loop can be passive, and it can dissipate the heat to the ambient by natural convection. The heat exchange area can be increased using heat radiators in a passive TMS. If the released heat is higher a forced primary cooling loop is usually needed. In this case the coolant or working fluid can be air or a water-glycol mixture in conventional cases or a dielectric fluid in a partial or total immersion cooling case. Fans are used to force the movement in case of gases and a pump in case of incompressible fluids. Battery cells can be exposed directly to air or dielectric fluid flows for prismatic or cylindrical cells. With pouch cells, some heat conducting pathways or heat sinks are used. Water-glycol mixtures require the use of some cold plates and thermal interface materials (TIM).

The secondary cooling loop can be also known as the active TMS. This active cooling is based on heat pump technology and uses refrigerant (VLE) as main working fluid in a closed loop. It is basically composed of a compressor, an expansion valve and two heat exchangers (condenser and evaporator). The evaporator extracts the heat from the primary cooling loop and the condenser dissipates it to the ambient. The condenser is normally a VLE/Air heat exchanger while the evaporator can be a WG/VLE or Air/VLE heat exchanger, depending on the coolant used in primary loop.

More details about conceptual design and particular cooling/heating components are given in D2.1.

4.4. Heating

For lithium-ion batteries, maintaining a temperature range of about 10 to 35 °C (50 to 95 °F) is generally considered optimal for operation and longevity.

Temperatures outside this range can lead to decreased performance, increased aging, and various safety risks [6].

So for the low temperature, some auxiliary heating is usually provided for thermal conditioning. In the case of SSB cells the minimum operative temperature is usually higher, so auxiliary heating is considered mandatory.

Heating can be provided directly using solid resistors close to the cells or indirectly using the primary cooling loop with an auto-regulable positive temperature coefficient (PTC) heater as can be seen in Figure 7.

More details will be given in D2.1.

4.5. Sensing and control strategy

Some feedback is needed from the battery system to check if the maximum and minimum temperatures are inside the best operative range, also ensuring their safety. This is done using some NTC thermistors placed strategically on the lateral surface of the cells or even on the busbars.

To have a good energetic balance working below ambient temperatures it is necessary to consume the less possible auxiliary energy from the cooling/heating groups. This objective is reached using well devised control strategies. The internal cooling loop is normally governed by the BMS depending on its temperature measurements using a simple on off strategy for the pumps or fans. The control strategy of the secondary cooling group is normally external to the BMS.

4.6. Interaction with other systems

The design and operation of the thermal management system will be the result of an interaction with the rest of the systems of the battery pack. In Figure 8 a sketch of these interactions is shown. From the mechanical architecture, the definition of the pressure control system will determine the constructive materials to be used, its geometry and lay-out. This will be part of the thermal path previously mentioned and will need to also fulfil the thermal requirements from the cells. In the same way, the geometry of the cell will condition the design of the thermal components. The mechanical integration of all the elements of the pack will also determine the geometry and size of the elements to be used in the thermal management system, as well as the thermal path through which the heat generated by the SSB will be dissipated.

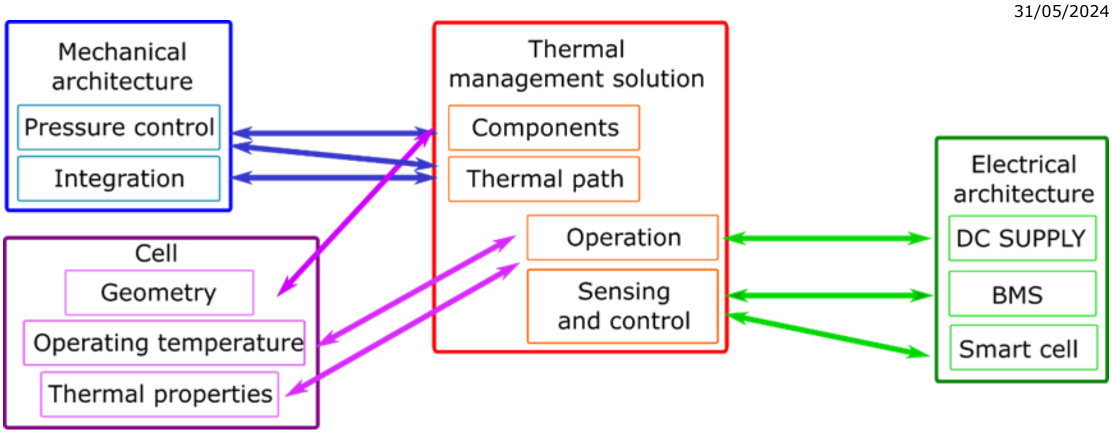

Figure 8. Boundary diagram of the interaction between the thermal management system and the rest

The electrical architecture is more related to the operation and control of the thermal management system. In the case of choosing an active cooling solution, the sensing required and the control logic will be handled by the BMS. Therefore, a proper connection and communication protocol will need to be used by the TMS components. The sensing capabilities of the smart cell concept that is going to be implemented in the project will provide the temperature information required for proper operation and control of the system. Finally, the cell thermal properties and operating temperatures will determine the operating conditions of the TMS.

5. Boundary diagrams

Battery systems can be connected in two different ways: in series or in parallel. Each method has its own advantages and disadvantages, depending on the application's specific requirements and constraints. Therefore, battery systems can also be connected using both methods to achieve better results.

5.1. Serial connection

Connecting battery systems in series provides higher voltage output, lower energy losses, wider inverter choice options, and simplified management.

However, connecting in series reduces redundancy; if one battery fails, the entire system's performance will be affected. Series connection also complicates battery expansion, as each new addition will affect the system's voltage output. Additionally, higher voltages are dangerous to humans, so such systems require much more attention to safety, making them more suitable for industrial uses.

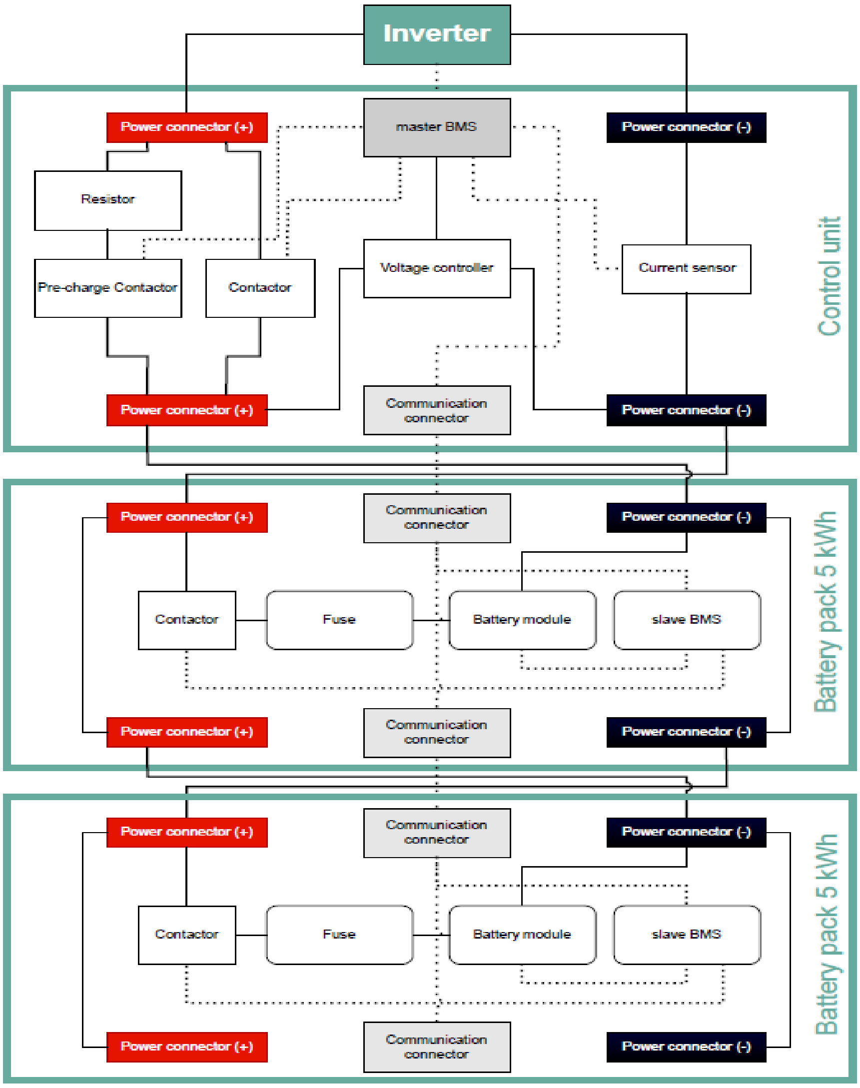

Figure 9 : Application serial connection boundary diagram of 10 kWh system

5.2. Parallel connection

Parallel connection provides higher capacity, redundancy and balanced charging. In case one battery fails or underperforms, the others continue to operate, providing redundancy and enhancing system reliability. Batteries connected in parallel tend to have more balanced charging and discharging characteristics since they share the load evenly. Adding more batteries to the system is straightforward, making it easier to expand the storage capacity. Lower voltages do not pose such a danger to human life, so it is more suitable for residential uses.

On the other hand, ensuring that all batteries have the same voltage and state of charge can be challenging, leading to imbalances and reduced efficiency. Managing multiple batteries in parallel requires additional monitoring and control to prevent issues like overcharging, undercharging, or uneven aging. Low voltage can be problematic looking from an efficiency point of view since it creates quite substantial heat losses compared to connection in series.

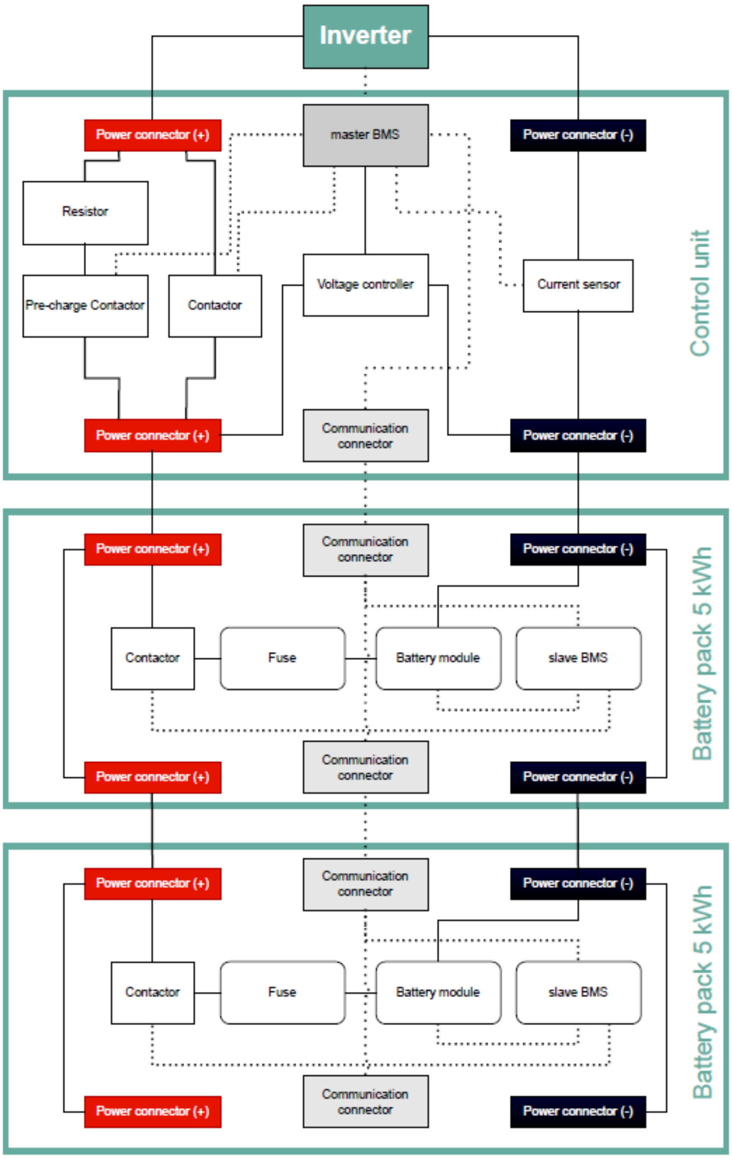

Figure 10 : Application parallel connection boundary diagram of 10 kWh system

6. Conclusion

The In conclusion, the EXTENDED project has made significant strides in advancing the design and integration of next-generation solid-state batteries (SSBs) for transport and mobile applications. The comprehensive analysis and development of the mechanical, electrical, and thermal interfaces outlined in this report demonstrate the feasibility and potential of SSB technology to meet the stringent demands of modern electric vehicles and residential energy storage systems.

The mechanical boundary diagram section highlighted the critical aspects of ensuring structural integrity, effective thermal management, and safety mechanisms. The detailed mechanical architecture, including the design of the housing, cell arrangement, bus bars, pressure control mechanisms, and venting solutions, showcases a robust framework capable of withstanding various operational stresses and enhancing the longevity and performance of the battery pack.

In the electrical boundary diagram section, we explored the high-level electrical architecture necessary for the efficient distribution and management of energy within the battery system. The integration of the Battery Management System (BMS), safety-critical interfaces such as the Battery Junction Box (BJB), and various converters (AC-DC, DC-DC) ensures seamless power flow and control, thereby optimizing the overall functionality and safety of the battery system.

The thermal boundary diagram section delved into the intricate thermal management strategies required to maintain optimal operating temperatures for SSBs. The deployment of both primary and secondary cooling loops, along with advanced heating mechanisms, ensures that the battery cells remain within their desired temperature range, thus preventing thermal runaway and other heat-related issues. The interaction between mechanical, electrical, and thermal components further underscores the importance of a holistic approach to battery system design.

Residential applications of SSB technology were also considered, with the analysis of serial and parallel connection configurations. These configurations provide insights into optimizing energy usage, enhancing system resilience, and achieving cost savings for homeowners. The versatility of SSBs in capturing excess energy, peak shaving, arbitrage, and providing backup power during grid outages highlights their potential to revolutionize residential energy storage solutions.

Overall, the deliverables of the EXTENDED project illustrate a cohesive and innovative approach to developing high-performance, safe, and scalable SSB systems. The detailed interfaces and design solutions proposed in this report lay a solid foundation for future advancements and implementations of solid-state battery technology in various applications. As the project progresses, continued collaboration and innovation will be essential to overcoming remaining challenges and fully realizing the potential of SSBs in transforming the energy landscape.

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