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NEXT-generation physics and data-based Battery Management Systems for optimised battery utilisation

NEXTBMS

NEXTBMS - Deliverable report

D3.1 - Battery module and -pack design

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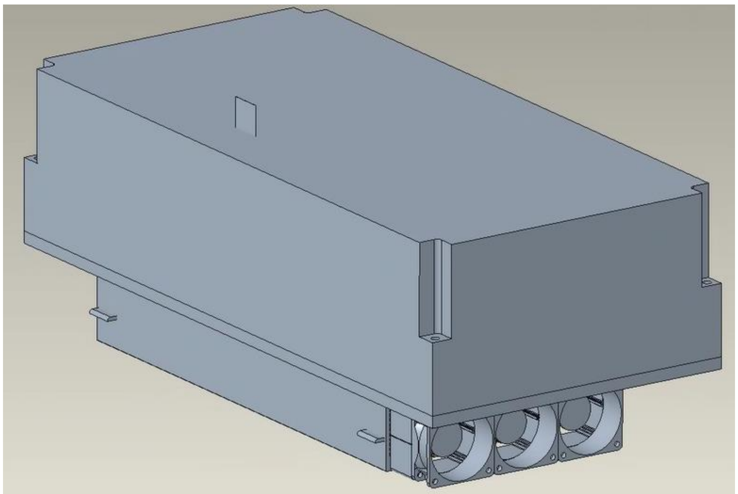
Project summary

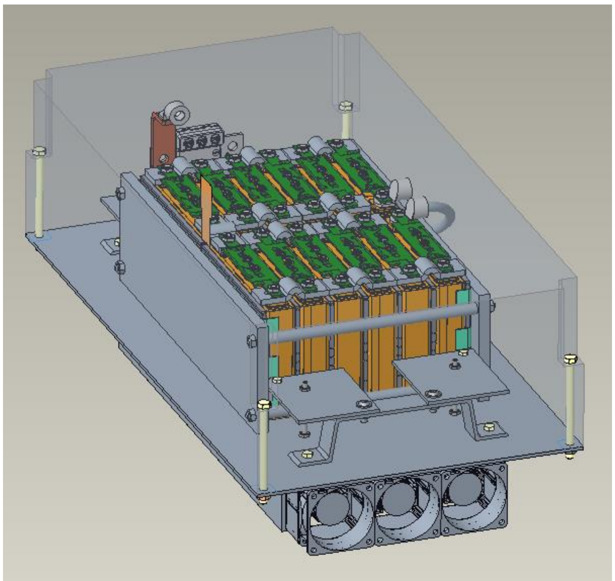
NEXTBMS will develop an advanced battery management system (BMS) built on fundamental knowledge and experience with the physicochemical processes of lithium-ion batteries, which will enable the significant enhancement of current modelling approaches, including the readiness for upcoming lithium (Li) battery material developments. These modelling approaches will be further improved by optimized sensors and measurement techniques to meet modelling needs (and optimising models based on physical sensor data) and the physical cell configurations to form a framework that supports improving the battery state prediction and control. By solving these challenges, NEXTBMS will ensure that the next generation of BMSs will enable higher performance, safety, and longer lifetime of the battery cells for an overall optimal utilisation of the battery system.

Publishable summary

Task 3.1 of Work Package 3 focuses on the comprehensive development of a battery module, encompassing cell selection, design development, and the integration of essential components such as sensors, thermal management systems, and electronics. The primary objective of Task 3.1 is to create a robust and efficient battery module for demonstrating the innovations the NEXTBMS project is aiming for. Therefore, generation 3b prismatic cells (with Nickel-Manganese-Cobalt (NMC) chemistry and a nominal cell capacity of 58 Ah) were selected as cells for the demonstrator. The design development process includes structural design for durability, electrical design for effective power distribution, and thermal management to ensure safe operation. Additionally, innovative sensor solutions are integrated to monitor critical performance parameters like temperature, voltage, and current, which are essential for further enhancement of the battery management system (BMS). The entire design is meticulously documented, detailing the sensor concept, thermal management strategies, and electronic components, ensuring the battery module is efficient, reliable, and well-documented for future reference and development.



Final NEXTBMS Battery Module Design



Module with transparent Top Housing Perspective

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Abbreviations & Definitions

Abbreviation	Explanation
A2D	Analog to Digital
Al	Aluminium
BCC	Battery Cell Controller
BJB	Battery Junction Box
BMS	Battery Management System
BOM	Bill of Materials
CAD	Computer Aided Design
CAN	Controller Area Network
CMB	Cell Monitoring and Balancing
Cu	Copper
CU HCP	High Conductivity Phosphorus-Deoxidized Copper
EE	Electrical Engineering
EIS	Electrochemical Impedance Spectroscopy
EMI	Electromagnetic interference
FLAE	Flexible Large Area Electronics
FBG	Fiber Bragg Gratings
FOS	Fiber optic sensing
GA	General Assembly
HV	High Voltage
I2C	Inter-Integrated Circuit
IC	Integrated Circuit
IP	Internet Protocol
LC-APC	Lucent Connector - Angled Physical Contact
Li	Lithium
MCU	Master Control Unit
NFC	Near Field Communication
NMC	Nickel Manganese Cobalt
OF	Optical fiber
PCB	Printed Circuit Board
PTC	Positive Temperature Coefficient
RFID	Radio Frequency Identification

rpm	rotations per minute
SBC	Single Board Computer
SEI	Solid electrolyte interphase
SoC	State of Charge
SoH	State of Health
SoX	State of X (e.g., Charge, Health, etc.)
USB	Universal Serial Bus
WP	Work Package

Item	Definition
Ah	Ampere hours
A_h	Heat transfer area
C	C-rate for Charge or Discharge Current (A) / Battery Capacity (Ah)
K	Kelvin
P	Power
T	Temperature
V	Volt
W	Watt
h	heat transfer coefficient, hours
kHz	Kilohertz
λ_B	Wavelength Bragg Grating (Lamda)
m, mm, µm pm	Length (Meter, Millimeter, Micrometer, Picometer)
m^3/h	Flow rate
m/s	Velocity
N_{fins}	Number of fines
Ω, mΩ	Resistance (Ohm, Milli Ohm)

1 Introduction

The project aims to enhance the performance and lifespan of battery systems through innovative physics- and data-based approaches. Enclosed to the core objective is to develop an advanced BMS solution that exceeds in performance, adaptability, and cost-effectiveness, Task 3.1 involves creating a new battery module with an innovative sensor system for enhanced cloud-based data analysis and more real-time battery insights. The 3D Computer-Aided Design (CAD) integrates advanced sensor hardware, such as fiber-optic sensors for precise temperature monitoring and a cell monitoring device enabling Electrochemical Impedance Spectroscopy (EIS) measurements. A novel communication concept ensures synchronized voltage and current tracking, enabling detailed diagnostics and supporting next-gen data applications.

This document outlines the design and development of a battery module, covering requirements, mechanical and thermal management, electrical layout, and sensor integration. In this project, a battery module containing 12 prismatic battery cells with Nickel Manganese Cobalt (NMC) chemistry was designed and developed, ensuring that all critical project requirements and design considerations are thoroughly addressed. The design process includes a comprehensive requirements analysis with input from all partners, including cell selection, mechanical design, and effective thermal management. The electrical design integrates safety concepts alongside a robust Battery Management System (BMS) and targeted control strategies. Additionally, we emphasize production aspects, while integrated sensors enhance diagnostics, contributing to improved BMS functionality and overall system efficiency.

The battery module was designed from the ground up to utilize new NMC prismatic cells, thus enabling comparison and cross-referencing with single cell testing and cell material data obtained in Work Package 2 (WP2). This approach was necessary because prismatic cells were chosen and the process from cell selection to assembly, was carefully considered to enhance performance and reliability while incorporating the latest advancements in battery technology.

2 Battery Module Design

In general, a battery module is composed of a group of cells assembled in different configurations to build more replicants to establish a final battery pack. The module design process is mainly based on some physical constraints, experience, customer expectations and cost. A module can include the following components:

- Parallel and series cells (power and energy)
- Cell-to-cell electrical connections
- Voltage and current sensors
- Temperature, pressure and/or strain sensors
- Mechanical structure to hold the cells, housing and protection
- Cooling system
- Control Board

Based on the target applications of the battery pack, some of the above-mentioned features may or may not be considered during the design procedure.

2.1 Battery Module Requirements

During the second General Assembly (GA02) meeting on 24.01.2024, AVL-TR presented a draft requirement document for the module design (list in Excel format) and all the Work Package 3 (WP3) partners discussed the different items mentioned in the initial draft. To narrow down the specifications needed for the module design concept all the WP partners worked collectively together to finalize the requirements. Following a unanimous decision by WP3 partners, AVL-TR finalized the requirement list to align with automotive standards. The created list then guided the design of the NEXTBMS battery module.

To enhance data acquisition from battery operations, advanced sensor technologies have been considered and integrated. These sensors are designed to ensure that the applied technologies do not interfere with the battery’s operation in terms of mechanical, electrical, electromagnetic impedance, or other potential influences. The goal is to achieve spatially resolved measurements of physical parameters (e.g. temperature) for each single cell. Therefore, minimally invasive sensor solutions, such as fiber-optical sensing and large-area electronics, have been implemented.

2.2 Design of NEXTBMS-Battery Module

The module is built-up on three levels:

- The 1st level is based on an aluminium boxed structure. By means of this structure, both the mechanical interface to the battery housing mounting brackets and the thermal interface between the cells and the battery module’s cooling system is achieved.

- The 2nd level includes the cell stack, connected via busbar connections, positioned through brackets carrier within the cell holder. Compression pads are added to the stack to counteract cell swelling. An upper aluminium frame is used for encapsulation of the module and mechanical support.

- The 3rd level hosts electrical and electronic engineering (EE) components and a plastic shield for the MCU. EE components will be placed at different levels to provide communication links among them and to the outside. The 3rd level is closely aligned with Task 3.2.

2.2.1 Mechanical Design of Battery Module

The module is composed of 12 prismatic cells connected in series with a 12S1P cell configuration using flexible busbars as shown in the following Figure 1. The reason for such a configuration mainly is because of more uncomplicated integration of the fiber optical sensors. This configuration has less edges resulting in less exposed fiber-optical sensors.

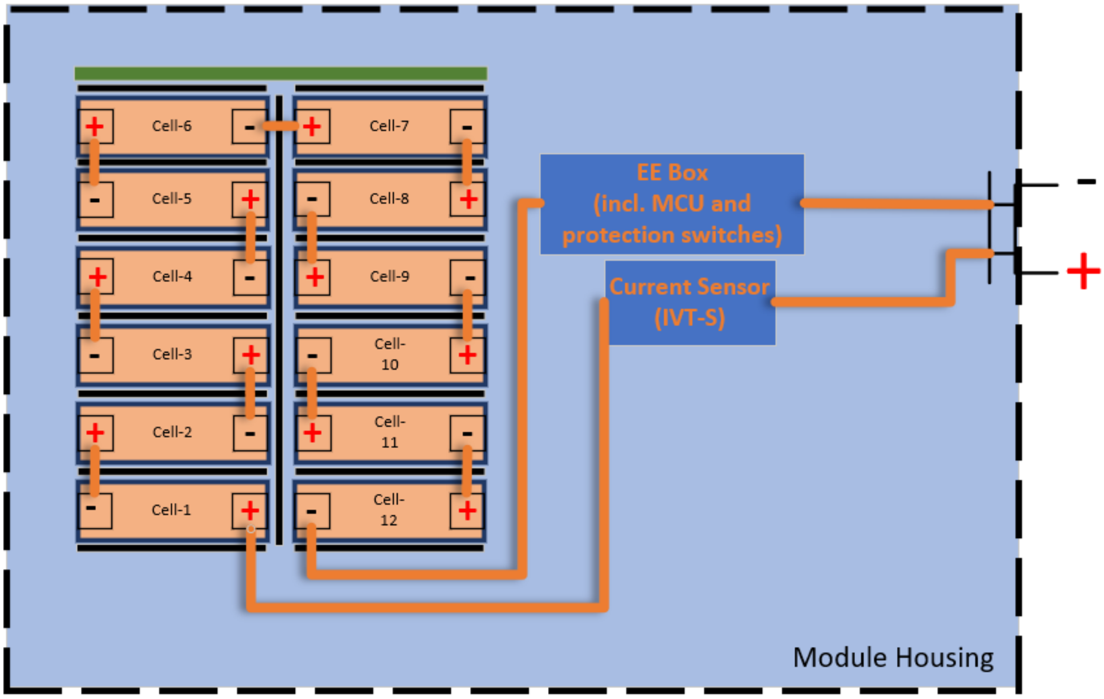


Figure 1: Cell Configuration in the NEXTBMS Module.

For the cell-to-cell connection, an initial discussion was made between the partners in which the advantages, disadvantages, and applications of the flat and flexible busbars were scrutinized. A summary is presented below:

- Structure and Material: Flat busbars are made of rigid and fixed metal bars, while flexible busbars are made of thin, flexible metal layers or braided wires.
- Applications: Flat busbars are used in stationary and high-current applications, whereas flexible busbars are used in areas with vibration and movement, and confined spaces.
- Advantages and Disadvantages: Flat busbars offer high current capacity and durability, while flexible busbars provide ease of installation and flexibility with lower current capacity.
- Cost: Flat busbars are generally more cost-effective due to their simpler manufacturing process and more economical material use. Flexible busbars are more expensive due to their complex production and design tailored for specific applications.
- Copper vs. Aluminium: Flat and flexible busbars can be made from either copper (Cu) or aluminium (Al). Copper busbars offer higher electrical conductivity and durability but are more expensive and heavier. Aluminium busbars are lighter and more cost-effective but have lower electrical conductivity and may require larger sizes to carry the same current as copper.

In addition, and maybe more NEXTBMS-relevant stiff busbars could disturb the sensitivity of strain sensors located between the cells. It will also bring in an asymmetry when swelling occurs. When exposed to swelling or temperature increase, prismatic cells usually bear a bent area on the busbar to compensate for the geometrical changes. According to the above-mentioned discussions a flexible busbar type is chosen for the cell-to-cell connection. Busbars for the prismatic cells can either be welded with support plates or can directly be screwed on using detachable bolts. For the NEXTBMS project the latter has been chosen to keep the flexibility of the design in case replacement of the battery cells or other components are needed in the future.

The busbar material used in the project is Laminated Copper with 0.2x24 High Conductivity Phosphorus-Deoxidized Copper CU HCP, the busbar itself is suitable for carrying currents over 180 A. The schematic design of the busbar is provided in Figure 2. The demonstrator module consists of 11 uniform busbars with a length of 63.1mm and a width of 24mm.

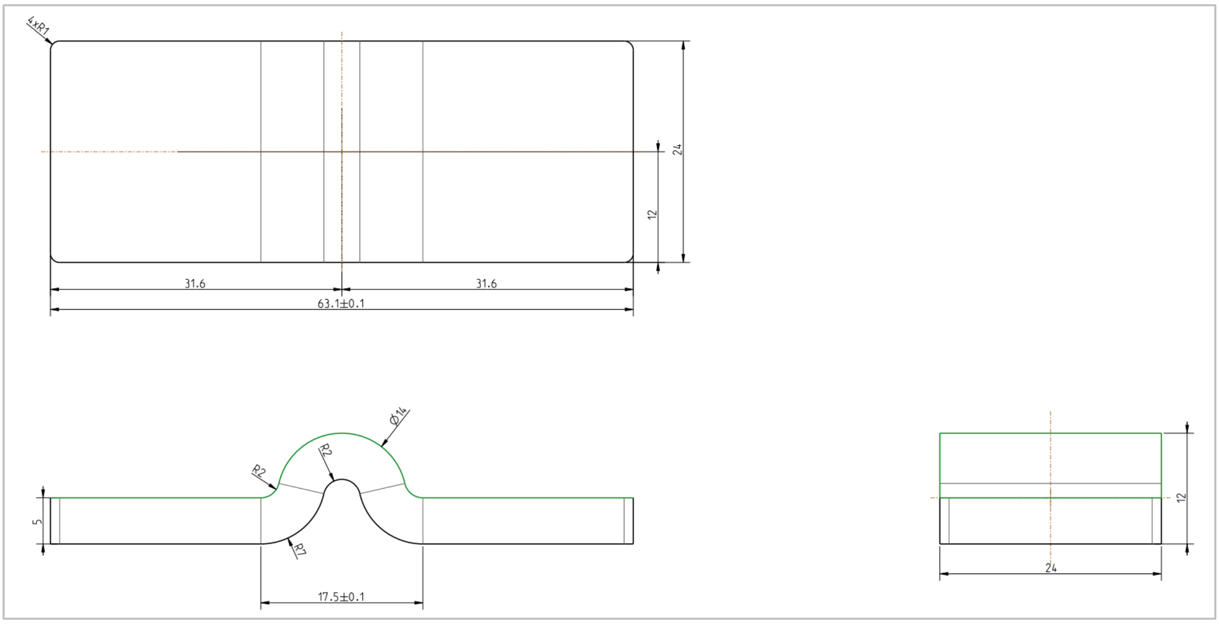


Figure 2: Unprocessed Busbar Design without Holes.

The overall cell stack with the corresponding compression pads is represented in Figure 3 with the corresponding components summarized in Table 1.

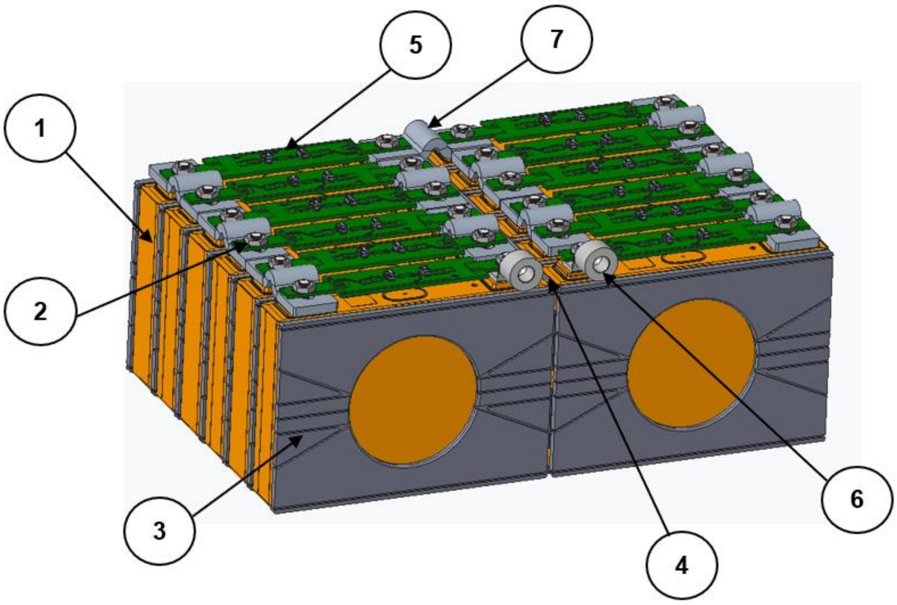


Figure 3: The overall Cell-Stack.

Table 1: Components for the Cell-Stack.

No	Part	Quantity
1	L148N58A Cells	12
2	M6X30 Hex Bolt	22
3	Spacer Plate/Soft Compression Pads	12/14
4	Middle-pressure plate	1
5	CMB (Cell Monitoring and Balancing)	12
6	Lug stud	2
7	Busbar	11

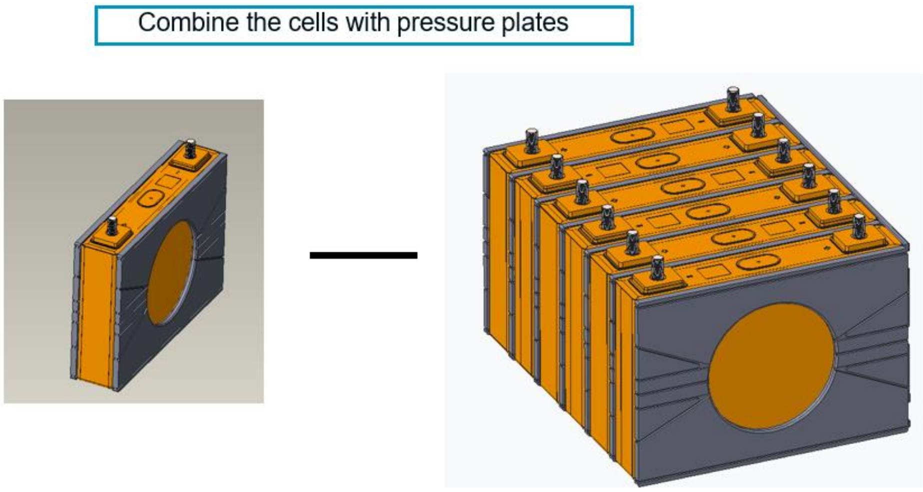


Figure 4: Arrangement of Pressure Plates Assembly Between Cells.

In Figure 4 the arrangement of the compression pads (pressure plates) is shown which are placed in between the cells. Generally, prismatic cells tend to change their thickness with respect to state of charge (SoC) and aging. In this context, for proper integration of the cells, the expansion of the cell needs to be considered and therefore the applied pressure on the cells should be kept within a defined range.

2.2.1.1 Mechanical Design: First Scenario

In the first version of the housing, the main frame of the battery module was constructed from an aluminium enclosure with slits for ventilation to cover the cell stack(shown in Figure 5). To ensure the secure installation of the frame, it has mounting points as well. Here, the top cover is used to increase the safety of the operator. The corresponding components of the housing are given in Table 2

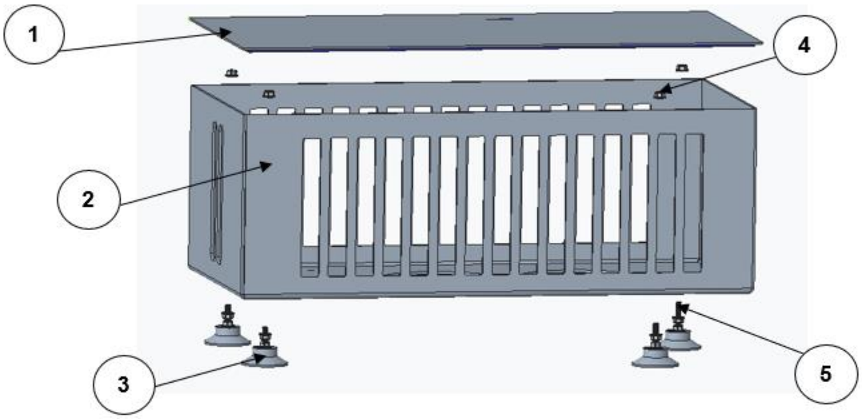


Figure 5: Initial Aluminium Frame with Slits.

Table 2: Components of the initial Frame.

No	Part	Quantity
1	Cover	1
2	Basement	1
3	Vibration Damper	4
4	M6 self-tightening nut	12
5	M6x35 threaded rod	4

According to Figure 6 the geometrical information of the designed initial version of the module can be summarized in Table 3.

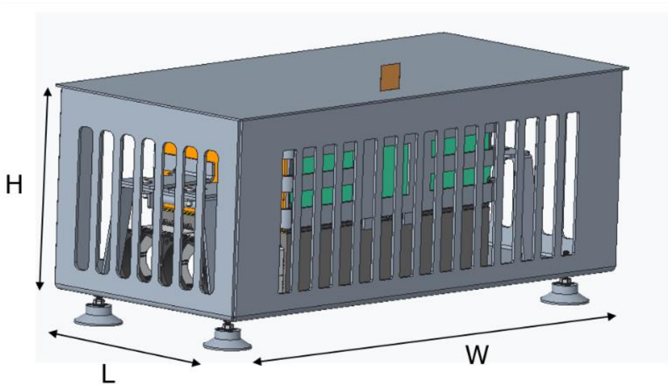


Figure 6: Initial Version of the Module with Cell-Stack Inside.

Table 3: Geometrical information of the initial Version of the Module.

Parameter	Value	Notes
Length	586 mm	335.5 mm without screw heads
Width	260 mm	
Height	235 mm	

To assemble and stabilize the cell stack, a bracket is designed as can be seen from Figure 7. First, a gap pad (depicted in green) is attached to the right and the left stabilizers. M6 Bars are connected to each other using the holes in the stabilizer. Before the bars are installed, they are passed through the pipes. The components of the outer bracket are given in Table 4.

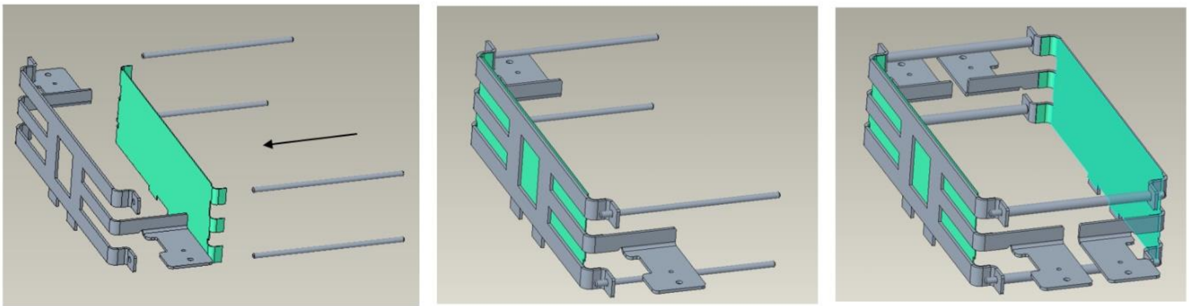


Figure 7: Cell-Stack Brackets and Stabilizers.

Table 4: Components of the Cell-Stack Stabilizers.

Part	Quantity
Left Side Fixer Bracket	1
Right Side Fixer Bracket	1
Gap Pad Brackets	2
M6 Bars	4
M6 Nuts	8
Pipes	4

The compressed cell stack in the outer bracket is shown in Figure 8. When mounting the cell stack between the stabilizers, the flex foil is sandwiched between the first row of cells and the gap pad. Using M6 nuts, bars, and pipes are tightened together and assembled. In the next step, busbars should be connected to the stud bolts in the cells and cell monitoring and balancing boards (CMB), and module terminal's cable lugs should be connected to the busbars. Finally, CMBs and cable lugs should be tightened to the cells using M6 thin nuts, as shown in Figure 9. The components are given in Table 5. To further integrate and fix the cell-stack into the housing, two side-bars are designed which are mounted to the bottom plate of the housing as shown in Figure 11. For this, M6 hex sockets (4X) are connected to the fixers from above, and the side holders are fixed from below with M6 nuts (4X).

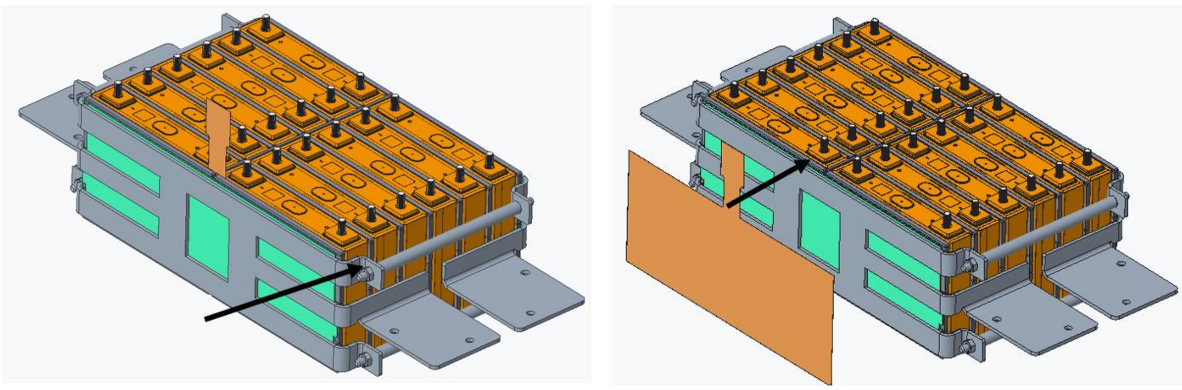


Figure 8: Cell Stack with Clamping Frame (left) and Cell Stack with Large Area Electronic Foil to be added at the stack end.

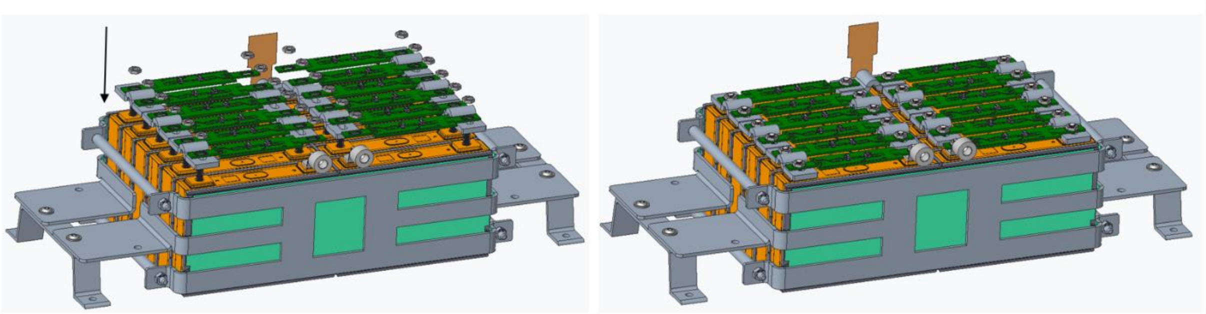


Figure 9: Assembly of CMBs on Cell-Stack, exploded view (left) and assembled view (right)

Table 5: Cell-Stack components inside the module bracket.

Part	Quantity
Busbars	11
CMB	12
M6 Thin Nut (ISO 4035)	24
Cable Lug	2
Side Holder	2

The mounting point of the CMBs to the cell stack is done via thin nuts with a thickness of 3.2 mm according to Figure 10. On the right side, the bottom and top view of the CMBs is depicted.

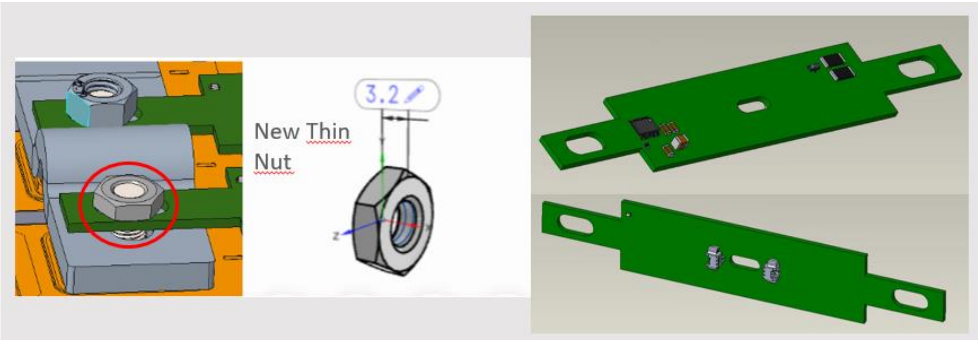


Figure 10: Assembly of CMBs with Thin Nuts (left) and CMB bottom view CMB top view (right).

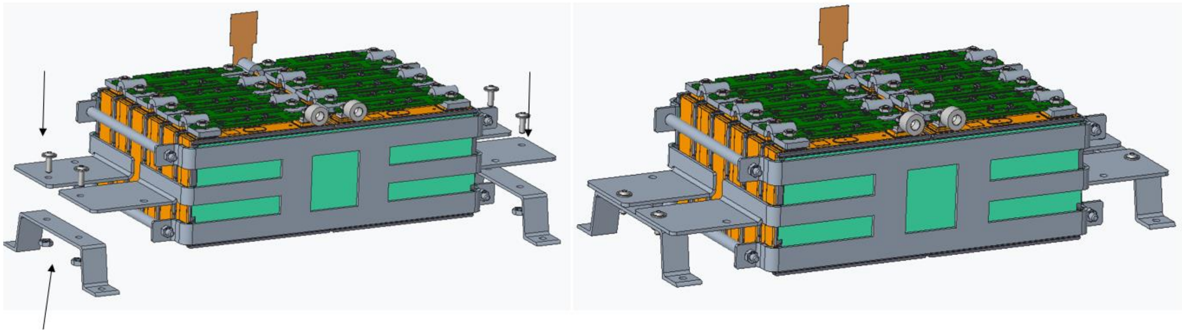


Figure 11: Fixation and Integration of Cell-Stack to Side Holders; left) Before Integration, right) After Integration.

According to the requirement list, since the battery cooling system is specified as air cooling using external fans and heat sink plates at the bottom of the module, before mounting the side holders to the bottom plate of the module housing, the heat sink with its integrated fans are placed and fixed as illustrated in Figure 12 (Bottom view). It should be noted that, in the first version of the heat sink design, an own heat sink design with 332 fins and two fans were considered (cf. Figure 12). Due to the challenges involved in manufacturing a heat sink with this large number of fins calculated (cf. section 2.2.2.2), it was agreed to purchase a ready-to-use heat sink with three fans (cf. Figure 13, Figure 23) by providing approximately 7 times the demanded maximum cooling power (cf. thermal management design in section 2.2.2.2).

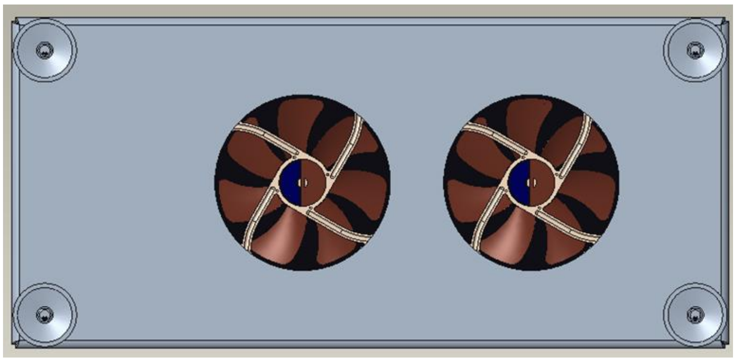


Figure 12: Bottom View of the Fans for Heat Sink (Initial design).

The ready-to-use heat sink is mounted on the bottom plate of the housing in a way that the cooling fans will face left, and the upper right and upper left corners will be placed in line with the stoppers which is shown in Figure 14, right.

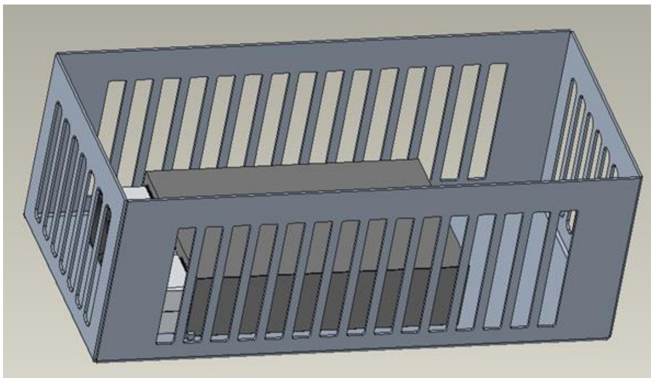


Figure 13: The placement of Heat-Sink inside the Initial Version of the Module Housing.

On top of the heat sink, a thermal adhesive glue with a thickness of 2mm is placed, which also is in contact with the bottom surface of the cell stack as depicted in Figure 14, left.

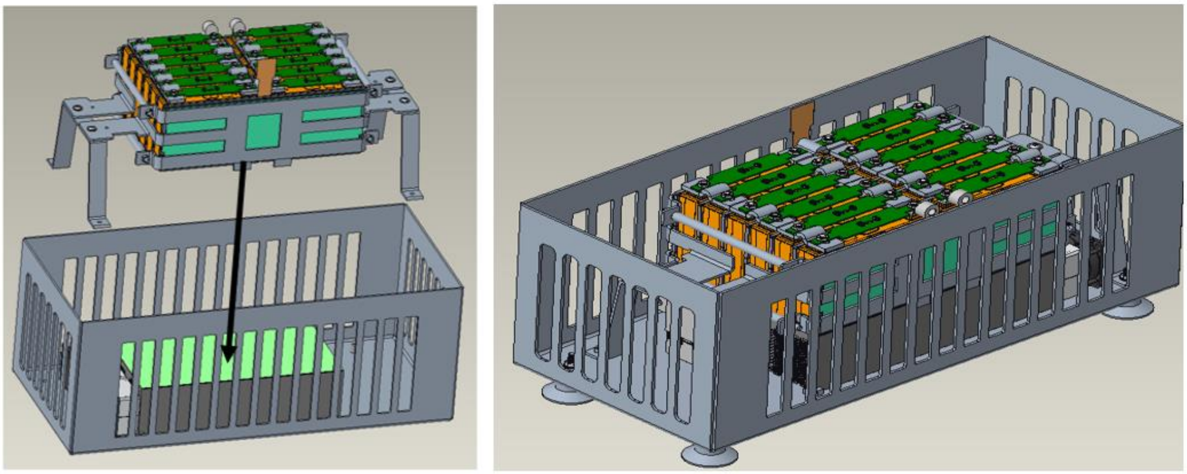


Figure 14: Left) Integration of Cell-Stack into Heat Sink with Adhesive Glue, right) Assembled Cell-Stack with Heat Sink.

The cell pack placed in the housing box must be fixed to the 2 damper pads on the left with an M6 self-tightening nut. The holder on the right must be fixed with an M6 hexagon socket bolt and an M6 self-tightening nut.

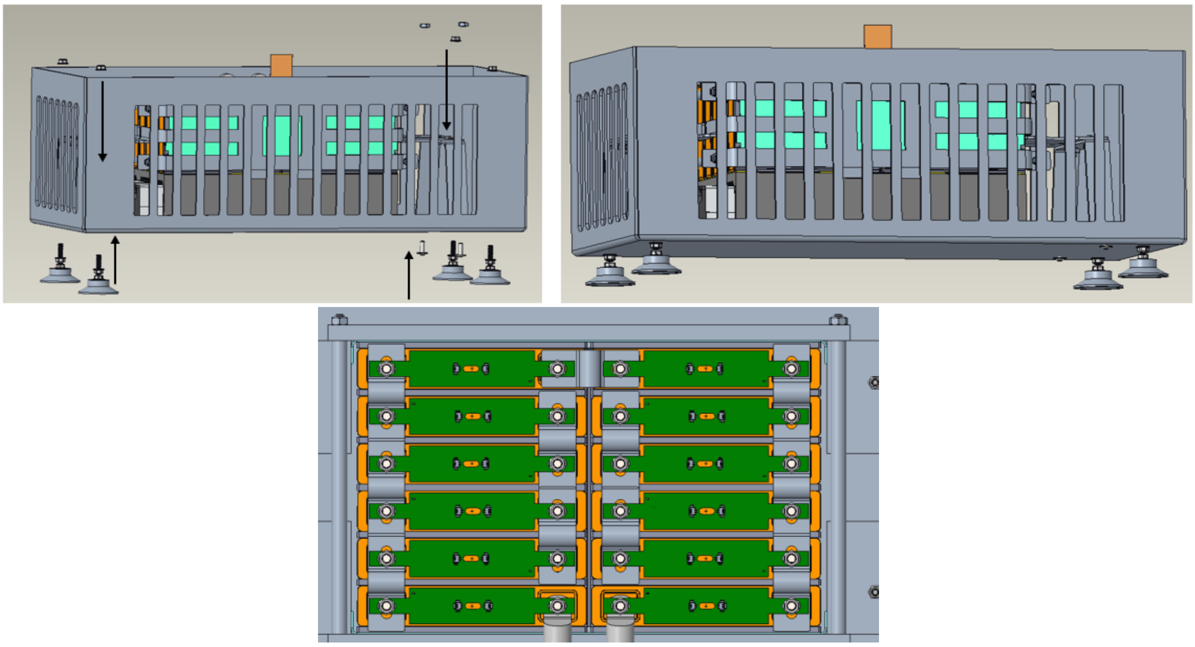


Figure 15: Top left) Stopper and Nut placement Top right) Module after Installing Stoppers Bottom) Top view of the Module without cover.

2.2.1.2 Mechanical Design: Second Scenario

To facilitate the assembly and components procurement for two complete battery module prototypes, the design was streamlined in a second design scenario to save further installation space and production costs. In this regard, according to multiple alignments between AIT and AVL-TR, and AVL-AT some modifications are performed, which took into account both the thermal management and housing optimization points. It should be noted that the steps for fixation and integration of the Cell-Stack presented for the first scenario also remain valid for the second scenario (cf. Figure 19).

As in the public deliverable D2.1 (Characterisation test results of physics-based cell models) reported [1], all cell tests are executed using external applied pressure of 100 kgF as specified in the datasheet. The force on each cell is applied by using pressure plates forced down by springs compressed to a specific height.

Therefore, as an initial assembly pressure the clamping forces applied to the cell-stack are set at 100 kgF. According to the investigations done by AVL-AT, the designed cell-stack bracket sheets from the first scenario may suffer from deformation issues and would bend assuming 100 kgF. To alleviate this problem, a thicker flat plate is designed and replaced with the sheet brackets, as depicted in Figure 16.

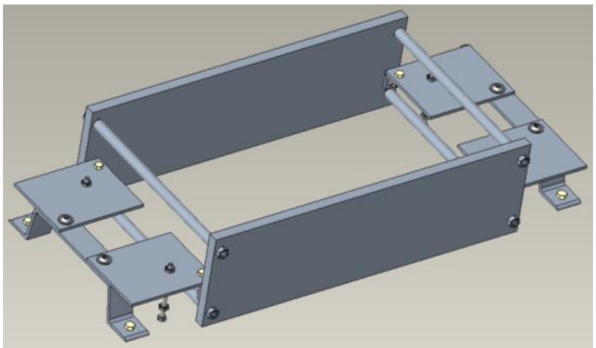


Figure 16: Refined End-Plates frame.

As elaborated below in section 2.2.2.2 on thermal management design, the ready-to-use heatsink provides 7 times higher cooling performance than the custom-designed 332-fin heatsink. This high cooling performance (approx. 3.5 kW) and the modification to remove the heat sink from the inside of the module housing to the outside of the module housing opens the possibility of simplifying the housing in such a way, that the housing design can be changed to one which is completely closed and does not have any slits on its surface. The top cover can therefore be realized by low-cost 3D printing. A further advantage of a fully closed module housing is a given robustness against external driven air flows which influences the heat transfer properties. The encapsulated housing ensures also the integrity of all installed components against dust, particles, accidental interventions by operators during handling, etc. Also, in case of a hazardous failure case, the housing protects the environment for a certain time against a dangerous situation (fire, electrolyte leakage, venting, flying particles). The flexible 3D-printed top cover, assembled with four screws, allows controlled gas leakage through gaps in case of venting, includes cable openings, and permits small permanent gaps without affecting heat transfer. To provide stability to all assembled cell stack components, the cell assembly and housing is attached on a stable and bending-resistant metal plate. Hence, this metal plate (Figure 17) is the mechanical basement and ensures the heat transfer from the cell stacks to the sink by conductivity.
Regarding the assembly or the module we expect for the second scenario better ease of access for manipulation.
To connect the closed frame with the heat sink, a base plate is designed. The base plate is shown in Figure 17 with its corresponding dimensions. The new structure of the module with the heat sink, is depicted in Figure 18, where the top side belongs to the closed aluminium frame, on the bottom of the frame the base plate is located and beneath is the heat sink with its fans. The general idea for this design is that the heat inside the closed frame of the battery module is transferred to the heat sink system via the base plate and the fans expel the heated air inside the heat sink.

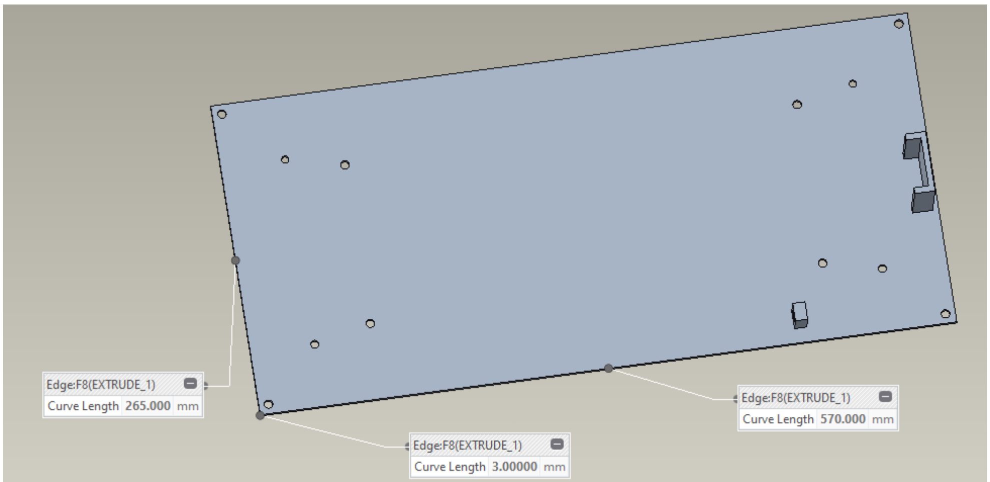


Figure 17: Designed Base Plate for Mounting Cell-Stack on the Heat Sink.

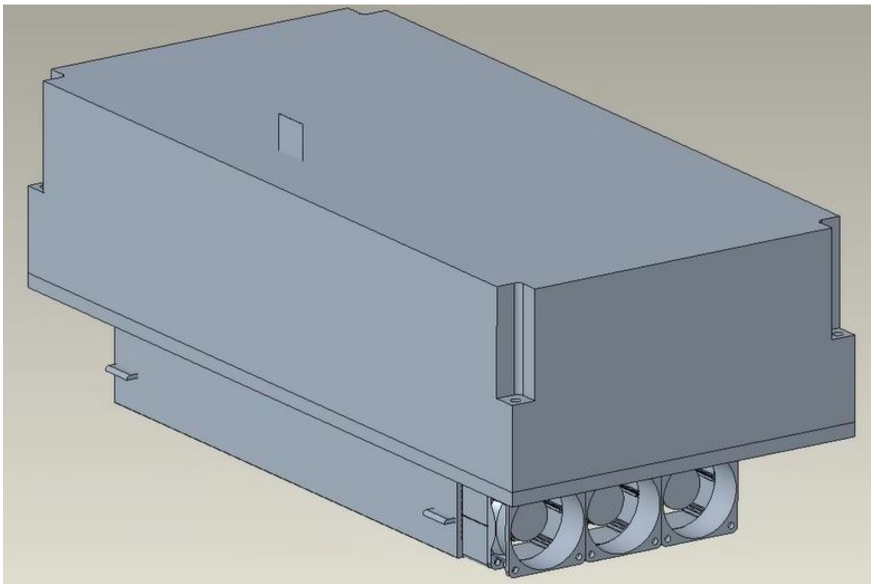


Figure 18: Whole Module Structure with Heat-Sink located Outside.

The integration of these three components (closed frame, base plate, and heat sink) is done by using both bars and nuts through the side holders of the battery brackets. As can be seen from Figure 19, the mounting between the cell stack brackets and the base plate is performed via 4 nuts through the side holders of the bracket. The base plate itself is mounted over the heat sink via 4 nuts as shown in Figure 20. To mount the top cover of the closed frame, 4 bars are integrated through the side holders of the housing brackets in the vertical direction. To better accommodate the cables connecting the battery lugs to the current sensor, a cable holder is designed on the base plate.

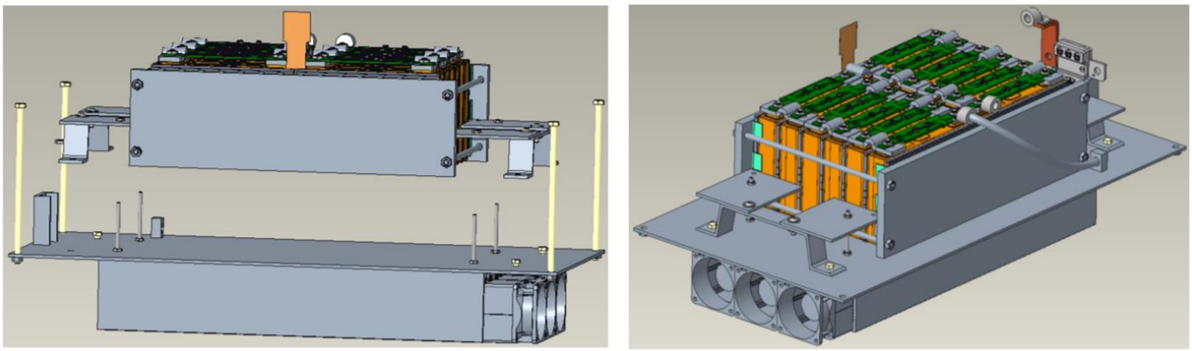


Figure 19: Integration of the Heat Sink with Cell-Stack using Side Holders and Base Plate.

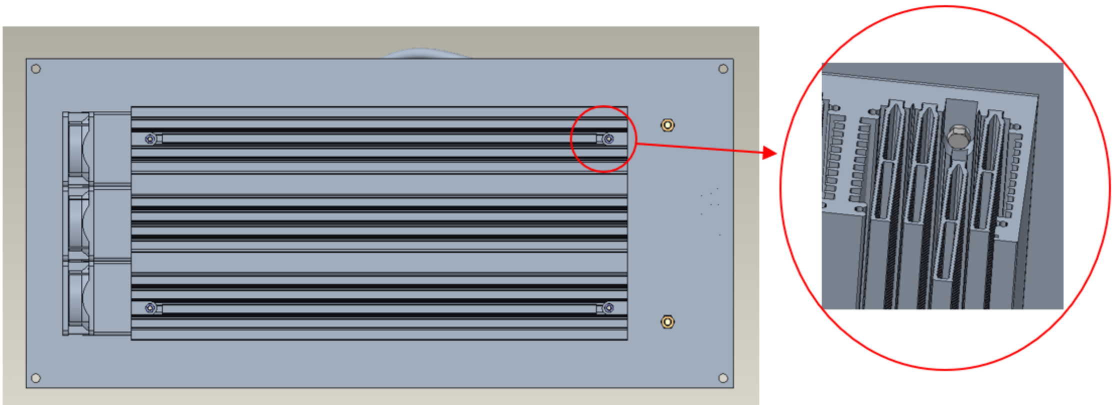


Figure 20: Heat Sink and Base Plate Mounting via Nuts Left) Zoomed View.

2.2.2 Thermal Management Design

2.2.2.1 Thermal Management Design Requirements

It should be noted that the battery module can only be optimally operated within a predefined temperature range. According to the request stated in the design requirements document, an air-cooling system is considered for the thermal management system. For this purpose, a heat-sink with specified number of cooling fins and external fans is included. The cooling system will be located on the underside of the battery module, separated from the cell assembly, and positioned outside the cell housing. The fans will be supplied via an external power supply.

2.2.2.2 Heat Sink and Air-Cooling Design

To design the heat sink required for the thermal management system in the module, first the dissipated power inside the module based on the continuous and fast charging scenarios need to be calculated. For the power loss calculations, some relevant parameter values according to the data sheet of the cell are summarized in Table 6.

Table 6: Electrical cell specifications.

Parameter	Value
Maximal Cell Voltage	4.35 V
Nominal Cell Voltage	3,7 V
Nominal Cell Capacity	58 Ah
C-rate for Continuous Charging	1.2 C
C-rate for fast Charging (10s)	3 C
Internal Resistance of Aged Cells	1.15 mΩ

The dissipated power for continuous charging can be calculated as:

$$P = RI^2 = 1.15 \times 10^{-3}\,\Omega \times \left(1.2\,\frac{1}{h} \times 58\,Ah\right)^2 \times 12 = 66.84\,W$$

Likewise, the power loss for the fast charging can obtained as:

$$P = RI^2 = 1.15 \times 10^{-3}\,\Omega \times \left(3\,\frac{1}{h} \times 58\,Ah\right)^2 \times 12 = 417.84\,W$$

If one considers additional 20 % power loss due to contact resistances such as busbars and electrical components inside the module, the total dissipated power for the fast-charging case will be equal to

$$P_d = 417.84 \times 1.2 = 501.4\,W \sim 500\,W$$

In the next step, the heat transfer coefficient should be calculated. For the initial design a system with two fans is considered with a fan diameter of 140 mm for each. The selected fan was NF-A14 industrial PPC-3000 PWM with an air flow of $269.3\ m^3/h$.

The flow area for the fan shown in the dashed red lines in Figure 21 is calculated as

$$\text{Flow area} = 2 \times \text{length} \times \text{fin height} = 0.0192\ m^2$$

with 300 mm heat sink length and 32 mm fin height [2]. The factor 2 considers the flow splits in two directions (cf. Figure 22).

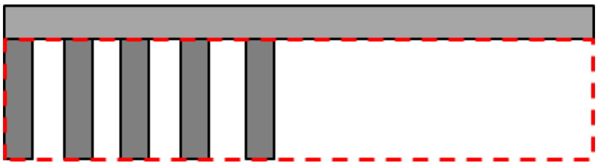


Figure 21: Flow Area for the Heat Sink.

Given the airflow of a single fan (Figure 22) and the flow area, the air velocity can be calculated as $7.234\, m/s$.

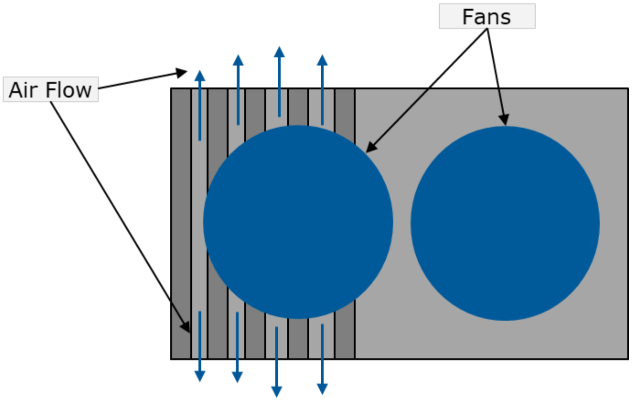


Figure 22: Air Flow for a Single Fan.

Based on the calculated heat loss P_d and the calculated air velocity and by assuming a convection heat transfer coefficient correlation flow over a flat plate the number of fins can be estimated [3]. Considering a Nusselt number and a hydraulic diameter for laminar flow conditions the heat transfer coefficient is estimated to be

$$h = 26.17\ \frac{W}{m^2 K}\ .$$

Assuming ΔT between air and heat sink of about 5 K (i.e. this means that the heat sink surface needs to be 5 K warmer than air to drive heat transfer) the heat transfer area can be calculated to

$$A_h = \frac{P_d}{h \times \Delta T} = 3.82 m^2$$

and the number of fins N_{fins} to dissipate a P_d of 500 W results to

$$N_{fins} = \frac{A_h}{A_{fin}} = 332$$

with

$$A_{fin} = 2 \times \text{width} \times \text{fin height} = 0.01152\ m^2$$

with 180 mm heat sink width and 32 mm fin height. The factor 2 considers that the fin is touching the air on both sides of its surface.
An alternative calculation assuming a convection heat transfer coefficient correlation for pipes based on Dittus-Boelter Equation [4] correlations show similar values, around 328 fins, which proves the calculations.
Based on the discussions between partners regarding the reduction of the heat sink fins and due to the fact, that the module will be operated within constant charge limits (1.2C) with occasional pulses (3 C for 10 s), the number of fins could be reduced by half or even by a factor of 3. Based on the

analytical calculation, the resulting up to three times lower heat dissipation $\left(P_d = \frac{500\,W}{2\ldots3}\right)$ would be still sufficient. This would result in approximately 110 to 170 fins, respectively.
Although the number of fins was reduced significantly, it was found that the fin-thickness in this design is only 0.5mm, which makes the heatsink extremely sensitive to handling and also very expensive in manufacturing. Due to these challenges, a second scenario was proposed by AIT and it was agreed to purchase a ready-to-use heat sink including three integrated 24 V fans [5] which are direct voltage controlled (0 V → 0 rpm, 24 V → max. rpm). This ready-to-use heat sink cooling system as depicted in Figure 23 (cf. also Figure 19, Figure 20) provides approximately seven times higher heat dissipation capacity compared to the previously proposedheat sink design with 332 fins. The ready-to-use heat sink considers also an extension in the plate for its fixation (i.e. by drilling a hole and fixing it with screws/bolts, cf. Figure 20).

Figure 23: Product Picture of the Heat Sink Cooling System PK 721-300-AL-D24V [5].

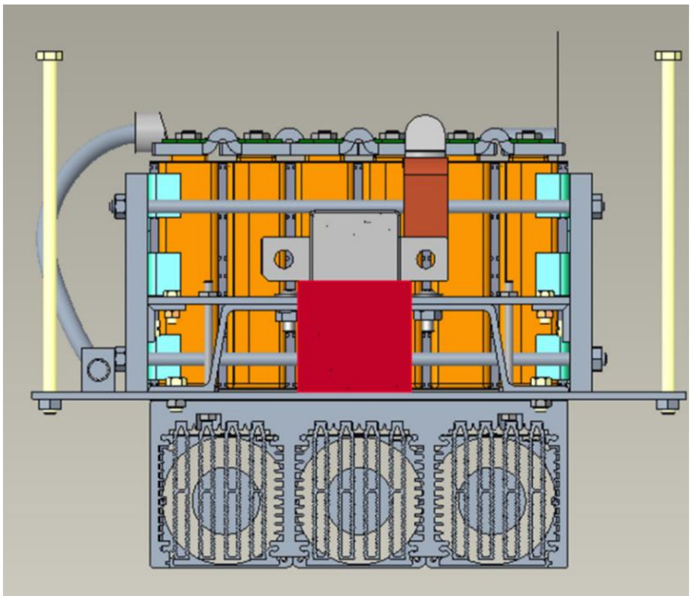


Figure 24: Front View of the Module with Heat Sink Cooling System.

2.3 Electrical and Electronic (E/E) Layout

As outlined in Figure 25 the BMS hardware encompasses of the monitoring and measuring components including current, voltage, and temperature sensors, and EIS measurement chip, along with integrated balancing circuits, solid-state based protection circuit, and most importantly a Master Controller Unit (MCU) which is responsible for the State-of-X (SoX) estimation, thermal management, and providing the overall control of the system via the Controller Area Network (CAN) bus communication. Figure 25 also shows the communication interfaces between components and MCU. The stepwise design of the CMB and main board is covered in deliverable D3.2: BMS HW design.

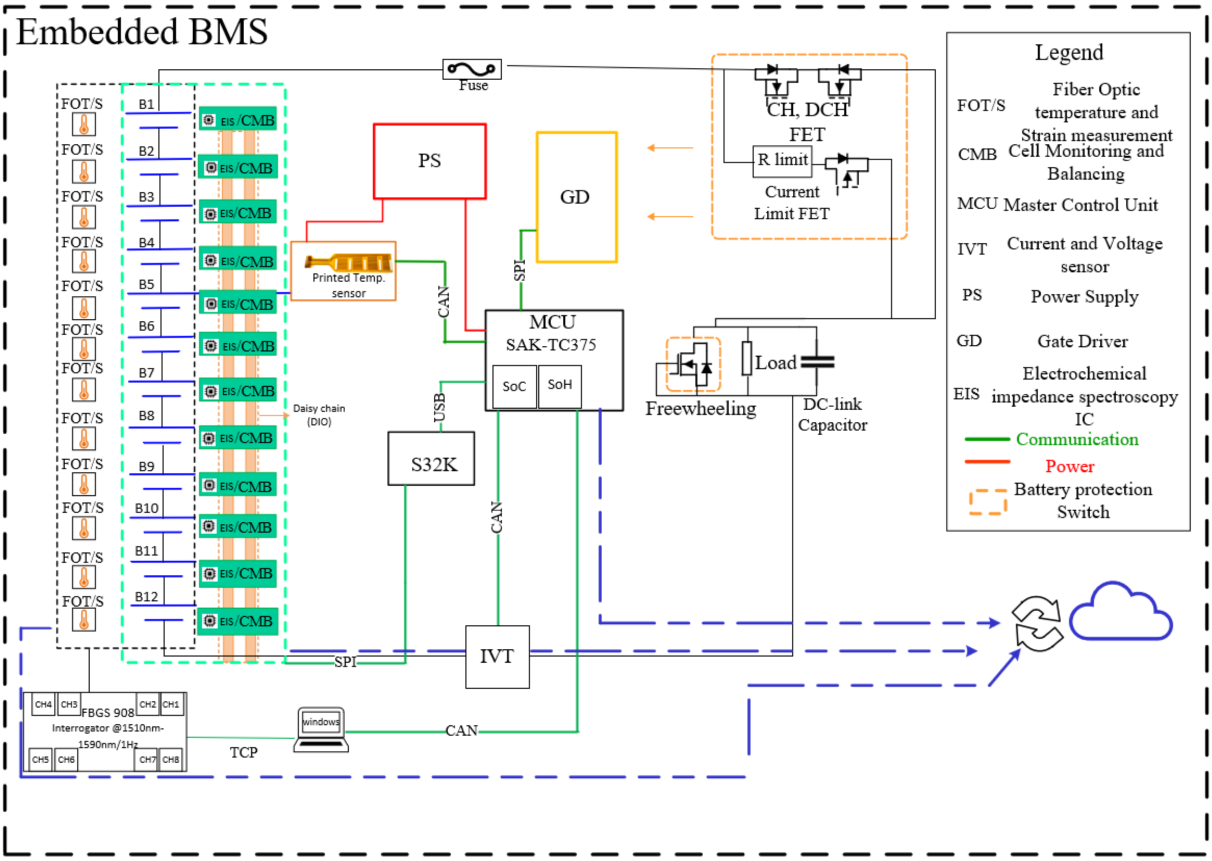


Figure 25: Single Line Diagram of NEXTBMS E/E Architecture.

2.3.1 E/E Design

The EE enclosure is securely positioned within a transparent plastic shield within the module houses that comprises both the main and slave boards. This setup includes three connection points: a Universal Serial Bus (USB) port facilitating communication between the slave and master control units, a power jack supplying the master control unit, and a CAN H/L header for CAN bus interfacing. Furthermore, the current sensor is located between the negative terminal of the battery module and the negative terminal of the load or charger. Additionally, from the front view of the module casing, the CAN bus interface and both negative and positive terminal ports are accessible as part of the user interface.

For the battery module an EE box is integrated into the module's structure. The EE box plays a crucial role in protecting and managing the electrical and electronic components of the battery module. It provides some functionalities like protecting sensitive electrical components from environmental factors, serving as a wiring hub inside the module and providing connectors for external interfaces. It is often customized to fit the specific requirements of the battery module. In Figure 26, from the front view, the EE box can be seen. From this figure, at the right side of the module, a box can be seen which is designed to protect the BMS. The purpose of this box is mainly to prevent electromagnetic interference (EMI) between the BMS and nearby electronic components, and furthermore to guarantee compliance with electromagnetic compatibility standards.

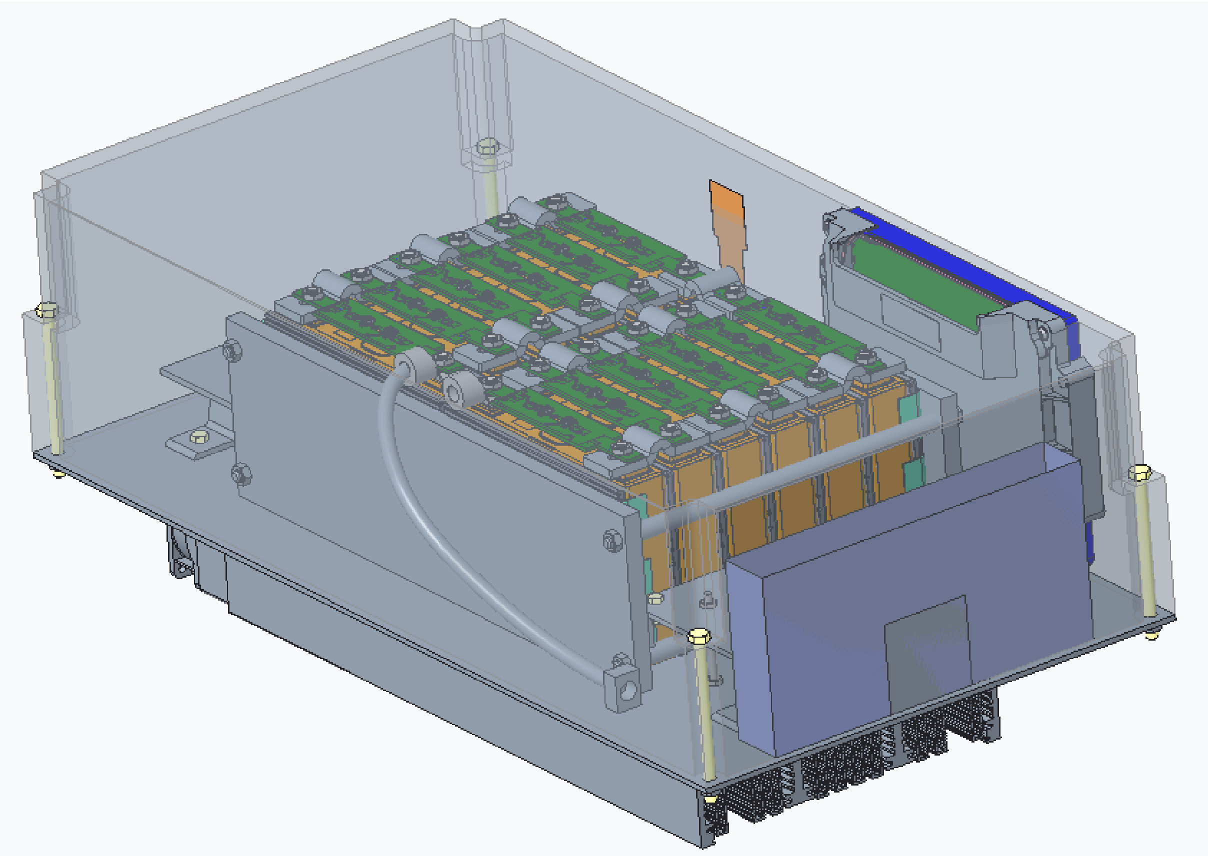


Figure 26: Draft picture dealing with EE enclosure boxes.

2.3.2 Sensor Architecture and Integration

Temperature sensing at specific locations on or inside the battery is crucial for state estimation. Heat generated within the cell is dissipated via conduction, convection, and radiation. Elevated temperatures can induce side reactions, compromising battery integrity, making effective thermal management essential. A sensor matrix capable of multi-point and distributed temperature measurement is desirable for spatially resolved data and diagnosing thermal inhomogeneities.

Volumetric deformation in lithium-ion batteries (LIBs) results from short-term cycling, long-term degradation, and abusive conditions. Pouch cells can increase in thickness by up to 4% during charging, while prismatic cells show about a 1.5% increase. Under abusive conditions, electrolyte decomposition can lead to gas generation and changes in cell volume.

Intercalation strain and cell pressure measurements are useful for monitoring battery performance and the dynamics of the solid electrolyte interphase (SEI), influencing the State-of-Charge (SoC) and State-of-Health (SoH). Consequently, a minimal invasive multiparameter sensor system, consisting of fiber optic sensors with diameters smaller than 180 µm and large area electronics with 200 µm thickness was integrated into the NEXTBMS battery design to monitor temperature, volumetric expansion, and other critical parameters. This data is essential for accurate SoH estimation and is transmitted to the BMS cloud for comprehensive analysis.

The placement of fiber optic sensors within the battery module is planned as one temperature sensor is used for every four battery cells, with each cell featuring five measurement points to accurately monitor temperature distribution. Additionally, a flexible large-area electronic foil, comprising 20 temperature sensing points, will be applied to one side of two cells. Throughout the entire module, all cells will be monitored for temperature and strain using fiber optic sensors. Also each strain fiber will cover four cells, with eight strain sensing points per fiber to track swelling in both the x and y directions so in total three temperature and three strain optical fiber (OF) sensors are applied. The fiber sensor readout will utilize a spectrometer-based FBG-Scan 908 interrogator, capable of simultaneously handling up to eight channels. In addition, large area electronic will be used to monitor the temperature distribution of the battery surface with over 20 measurement points. Both sensor technologies will be connected to the CAN-BUS.Advanced SoX calculations using EIS require precise voltage and current measurements.

2.3.2.1 *Fiber Optical Sensors*

2.3.2.1.1 Fiber Optical Sensor Principle

Fiber optic sensing (FOS), also known as fiber-optical sensing or OF sensing, is a technology that utilizes light guided through an optical fiber and manipulated within optical elements or sometimes within the fiber itself. After manipulation, the light is analysed to evaluate the desired parameters. This manipulation of light can occur in terms of intensity, wavelength, phase, polarization, and other factors. These sensors offer key advantages over electronic systems, including small size, resistance to electromagnetic interference, no need for electrical power at remote locations, chemical stability, and compatibility with harsh environments like the in-situ application for the battery module. Fiber Bragg Gratings (FBGs) [6] are created by exposing the core of a single-mode optical fiber to a periodic pattern of intense laser light, resulting in a permanent increase in the refractive index, forming a grating (cf. Figure 27). The principle behind FBGs is Fresnel reflection, where light traveling between media of different refractive indices reflects and refracts at the interface (cf. Figure 28). This induces coupling between two modes when the phase-matching condition is met, reflecting the Bragg wavelength while transmitting the rest of the spectrum.

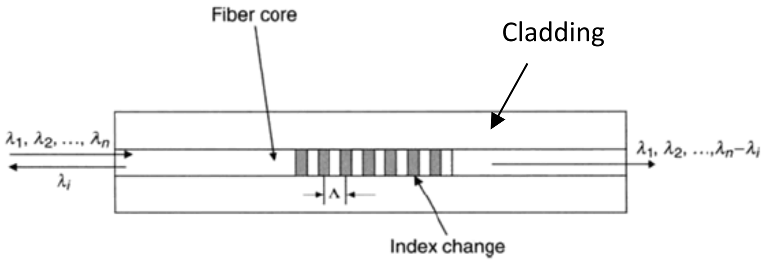


Figure 27: Schematic of a Fiber Bragg Grating with in a Single Mode Fiber [6].

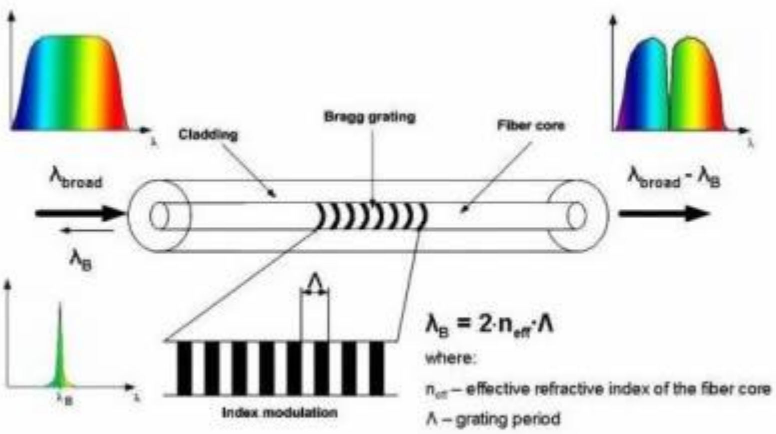


Figure 28: Working Principle of an FBG. A Broad Band light Pulse is sent into an OF. A certain wavelength (Bragg Wave Length λ_B) is reflected [6].

FBGs are highly sensitive to strain and temperature, as these factors change the grating's periodicity and the fiber's effective refractive index. The wavelength shift in an FBG can be expressed as a function of strain and temperature changes. This sensitivity allows for precise measurements of these parameters, making FBGs valuable for multiparametric and spatially resolved fiber-optic sensing. FBG sensors typically operate with a central wavelength of around 1500 nm, with temperature sensitivity coefficients of about 10 pm/K and strain sensitivity of 1-2 pm/με.

2.3.2.1.2 OF Sensor Implementation in Battery Module

In the battery module, FO sensors are installed across multiple cells to measure temperature and strain. Each cell has five temperature measurement points distributed as shown in Figure 29, and two strain measurement points in the x and y directions, also depicted in Figure 29.

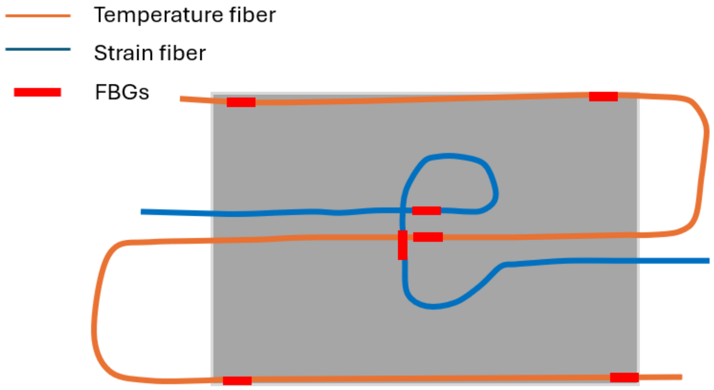


Figure 29: Rough Fiber Routing of Temperature and Strain Fiber and intended FBGS Positioning

The fibers used in the battery module have a cladding diameter of 125 µm, making them very small and minimally invasive. However, to prevent damage, even pressure on the fibers should be avoided. Therefore, spacers are used between cells for fiber routing and to avoid fiber damage. This spacer shape shown in Figure 30 a) allows for universal application on every cell in the module, aligning with the cell stack mounting and cell fixtures in the module, as shown in Figure 30 b).

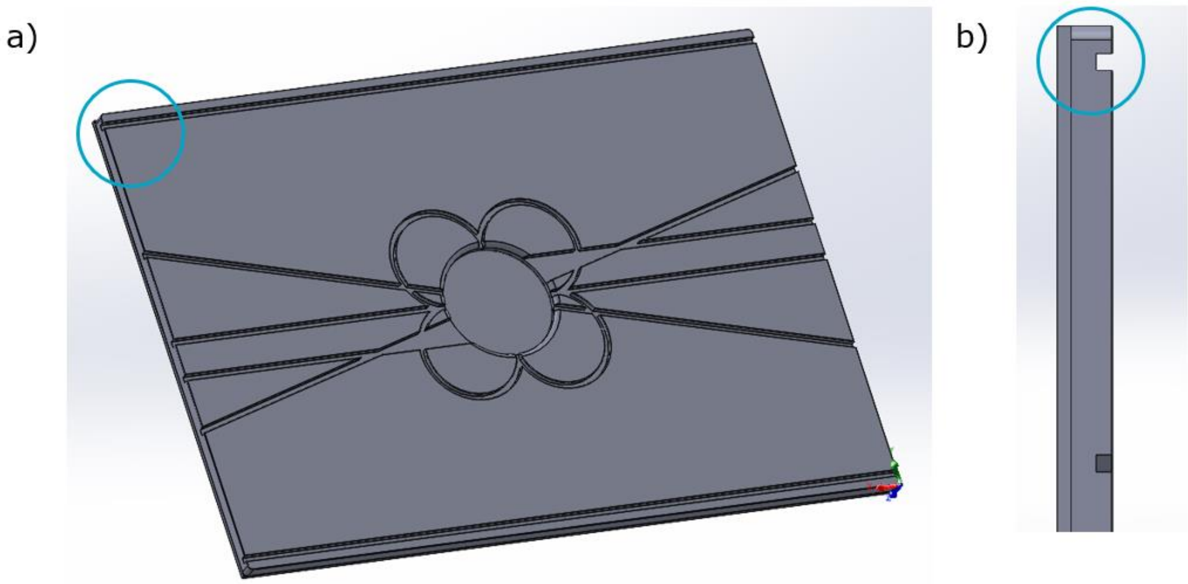


Figure 30: Design of the Spacer for a safe Fibre Placement between the Cells a) Full Design with vertical and diagonal Cavities b) Side View of upper Region of Spacer with Groove Slots.

Also, Silicone PORON® Polyurethane patches are integrated between the cells and spacer utilized for its high thermal stability, flexibility, and electrical insulation properties. They are used to cushion and protect the battery cells from mechanical stress and vibrations.

For accurate temperature measurement, it is crucial that the FBGs of the temperature fibers are decoupled from strain and pressure forces at the sensing spot. Therefore, fibers are guided with small capillaries glued close to the battery surface to maintain their placement while ensuring a rapid temperature response time. The capillary is adhered to the designated sensing spot, and the fiber itself is freely sliding within the capillary.

To optimize heat transfer and minimize the influence of micro strain, various capillaries with different materials and diameters were investigated in a climate chamber test. Fibers were placed in strain channels and different capillaries, designed similarly to the temperature fiber planned for the NEXTBMS battery cell, and heated within the expected temperature ranges of the battery module. In Figure 31, temperature curves are shown for silica capillaries with an inner diameter of 250 µm and outer diameter of 350 µm (a), and an inner diameter of 150 µm and outer diameter of 363 µm (b). Additionally, a stainless steel 1.4401 capillary with an inner diameter of 250 µm and outer diameter of 800 µm is depicted in Figure 31. As a reference, one fiber was placed inside an aluminium block to test long-term temperature stability and to avoid temperature deviations from the climate chamber.

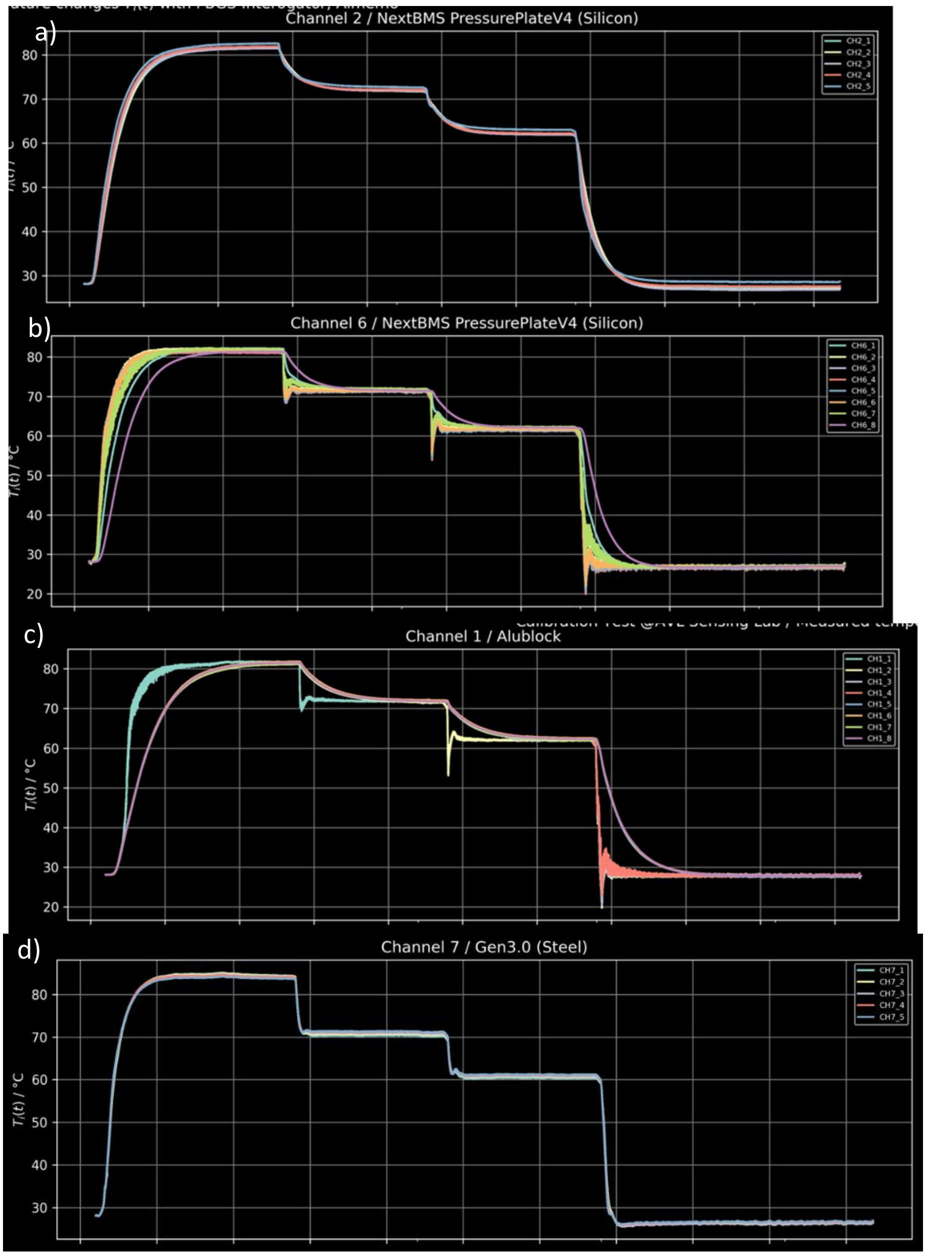


Figure 31: Temperature Curves and Measurement Results of Temperature Fibres placed in the Climate Chamber fixed in different Fibre Routing Approaches a) Silicon with ID 250 b) Silicon with ID 150um c) Aluminium block d) Stainless steel Capillary.

Capillaries made of silica and with an inner diameter of 250 µm appear to be the most promising solution for the battery module. The strain fibers are mounted directly to the surface of the battery cell using an epoxy resin adhesive. However, for accurate strain measurement, it is crucial to decouple temperature influences from the strain fibers. Therefore, during data interpretation, the temperature measured by the central FBG temperature sensor in the middle of the battery is used to account for and exclude temperature effects on the two strain sensing spots.

The final arrangement of fibers in the module is as follows: Generally, one fiber is utilized for four batteries, providing 20 temperature measurement points on a single fiber routed over four batteries. Additionally, eight strain sensing spots are distributed across four batteries. Each battery cell has five temperature sensing points, as illustrated in Figure 32: Final Arrangement of Temperature and Strain Fibers in the Battery Module.

Two strain fibers are oriented in the x and y directions to measure strain influences (battery breathing). Furthermore, one temperature sensor is required for better temperature decoupling on strain sensors, as temperature influences also induce strain on the fiber. Spacer and battery compression pads are placed between every cell and at the two end cells where fiber optical sensors are attached.

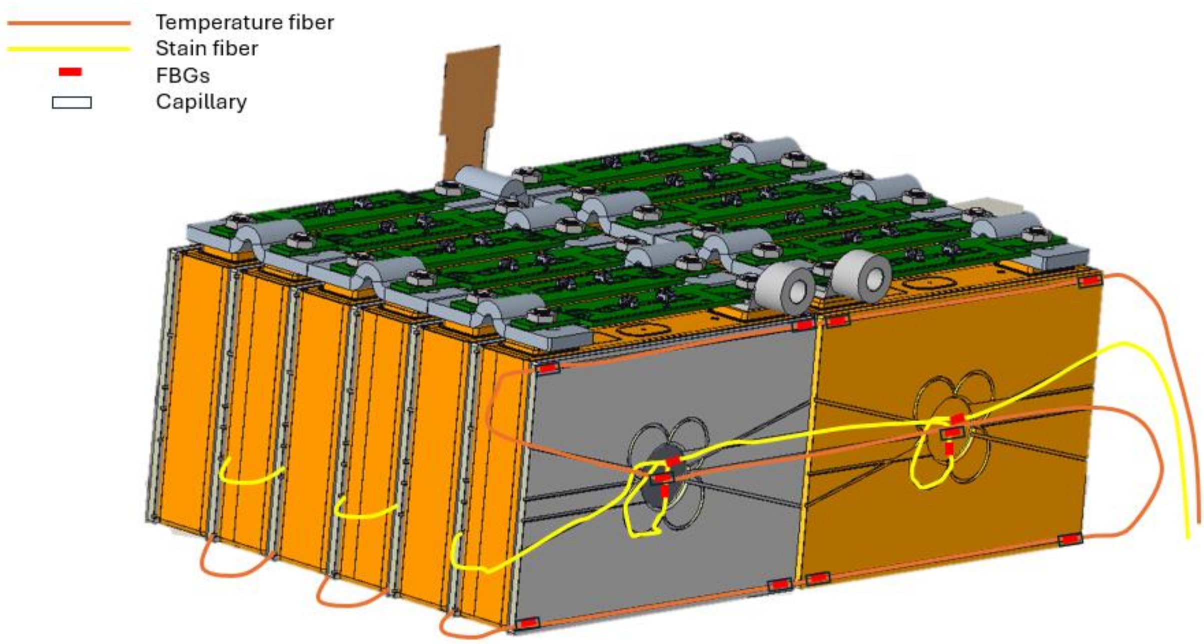


Figure 32: Final Arrangement of Temperature and Strain Fibers in the Battery Module.

The fiber connection to the interrogator is established using LC-APC (Lucent Connector - Angled Physical Contact) connectors. However, it is also feasible to utilize FC adapters to extend the fiber cable, providing a more cost-effective and reliable optical connection for secure signal transmission over longer distances.

2.3.2.2 *Flexible Large Area Electronics*

Flexible Large Area Electronics (FLAE) is a cutting-edge technology that involves the integration of electronic components on flexible substrates. This allows for the creation of large, bendable, and lightweight electronic devices that can conform to various shapes and surfaces. FLAE technology is particularly advantageous in applications where traditional rigid electronics are impractical. The flexibility of these sensors allows them to be placed in close contact with the battery cells, providing real-time temperature data that is crucial for effective thermal management. This ensures that the battery operates within safe temperature limits, preventing overheating and enhancing the overall performance and lifespan of the battery module.

2.3.2.2.1 Description of Flexible Large Area Electronic Technology

The sensor principle (cf. Figure 33) involves a large area electronic temperature sensor that operates based on the Positive Temperature Coefficient (PTC) effect. In PTC sensors, the resistance of the sensor material increases as the temperature rises. This characteristic makes PTC sensors suitable for precise temperature measurements over large areas. The basic working principle of resistive sensors, including PTC-based temperature sensors, involves the following steps: When a temperature stimulus is applied to a sensor, the sensor's resistance changes in response to the temperature variation. For PTC sensors, resistance increases as temperature rises due to the material's properties. This resistance change is then converted into an electrical signal from the thin printed electronic, which can be measured to determine the temperature [7].

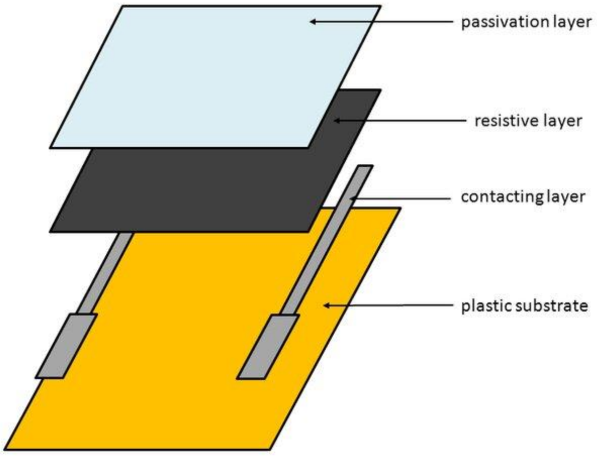


Figure 33: Principal Design of the printed Temperature Sensor [7]

2.3.2.2.2 Specification of implemented Foil

The flexible electronic foil, measuring 252x120 mm, incorporates 24 PTC temperature sensing spots. These spots are strategically distributed, with 12 sensors covering each of the two cells in the module arrangement. This configuration enhances the temperature distribution monitoring of two batteries, particularly on one side without fiber optic sensors. The adaptable CAN interface facilitates direct communication with BMS cloud, ensuring seamless integration. Additionally, the foil can be easily applied using optional double-sided adhesive tape.

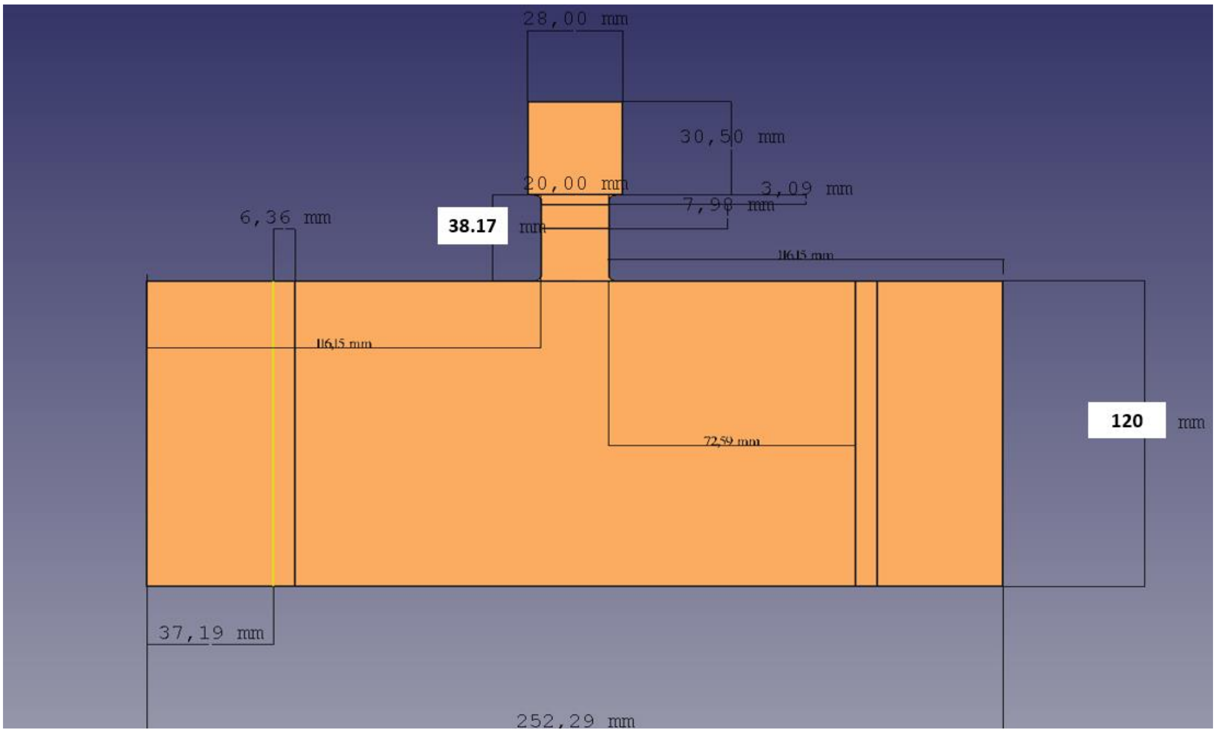


Figure 34: Dimensions of Large Area Electronic Temperature Sensing Foil.

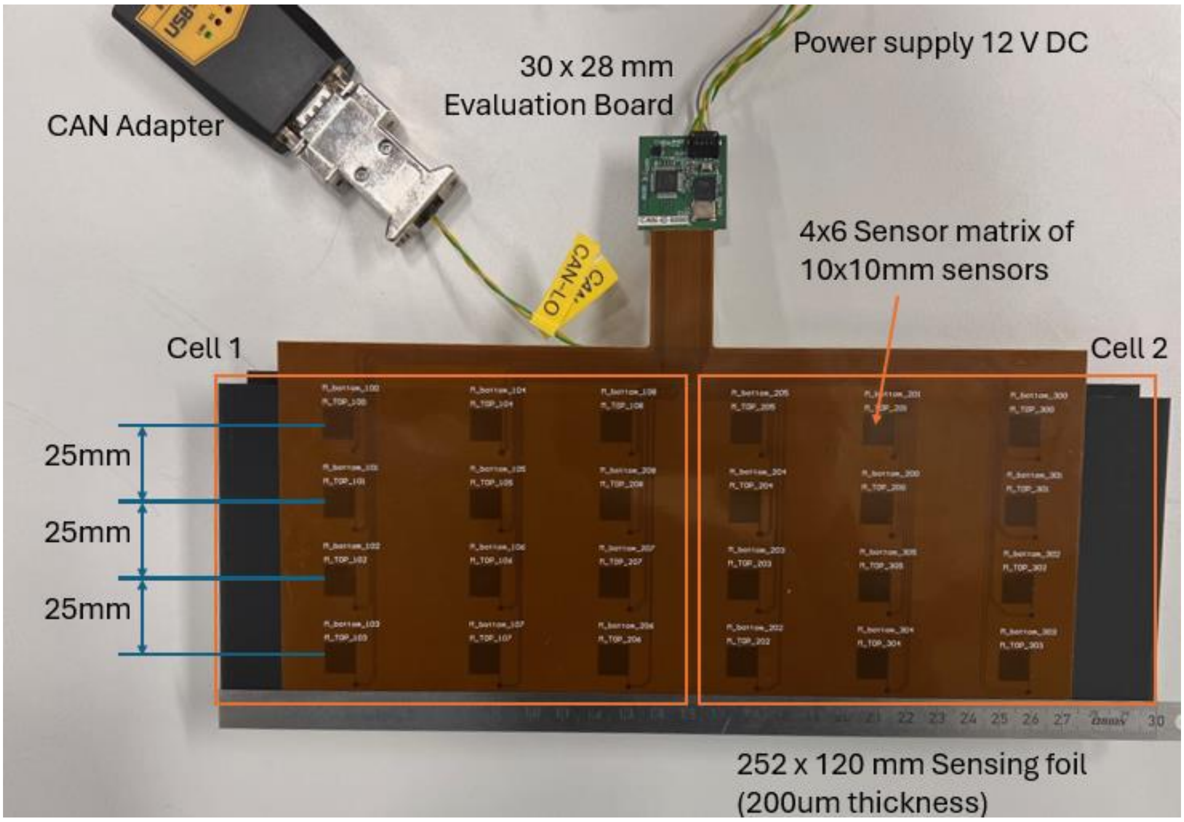


Figure 35: Placement on 2 cells and position of Temperature Sensing Points.

2.3.2.2.3 Sensor interface of FBG and LAE

A rough information processing flow diagram from the optical measurement approach (FBG) is depicted in following diagram:

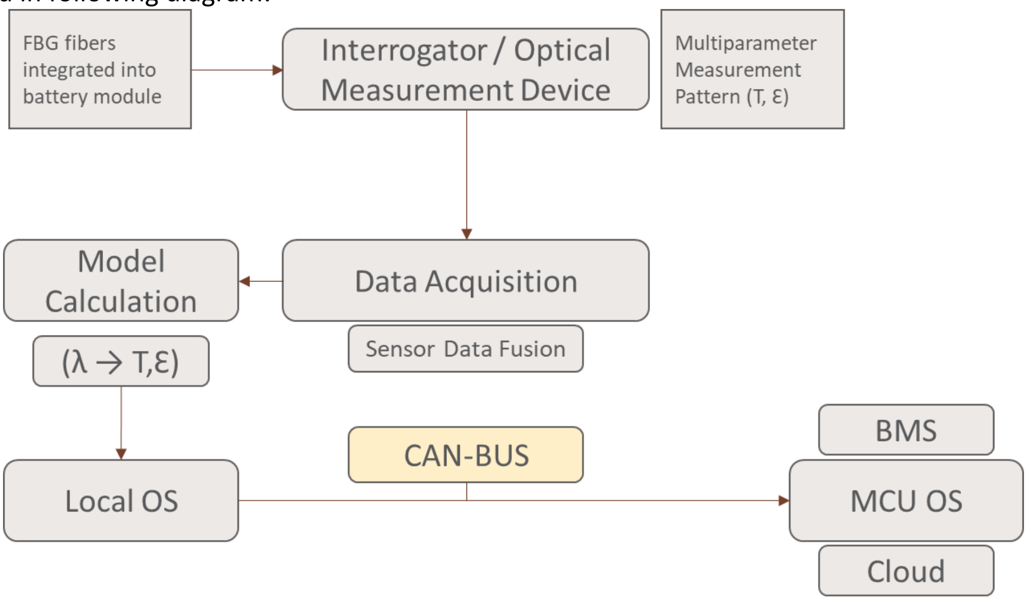


Figure 36: Data and Information Flow Chart for FOS.

The raw wavelengths λ will be measured by the optical measurement device (Interrogator) in parallel by all used channels and the data will be forwarding via a serial connection (USB-B) to the Illumisense Software API (FBGS) on the local measurement PC based on a Windows Operating System. For enhancing optimal automation and fast re-calibration processes a Software wrapper is written in Python. The implemented Illumisense Connector class initializes automatically all channels with the given sensor configuration file. This is just a static JSON file that includes the number of sensor points, temperature and strain assignment of channels, calibration parameters etc. Additionally, the wrapper fetches the raw data from the Illumisense Software TCP socket, converts it to the according temperature and strain values and partition the data in a memory-saving manner for the CAN-Bus

interface. Here the USB-CAN connector from Peak Performance is used together with the open-source library Python-CAN for forwarding the data to the MCU.
Based on discussions with the project partners we decided to use a Sample rate of 1 Hz on the Optical Sensing approach which will result consequently a cyclization time of around 1000 ms of the message blocks to the CAN-Bus (slight delays can occur due to the computational expenses).
In the following Figure 37 there is the physical connection diagram shown. One can see the individual channel rooting to the batteries. As already described, 4 channels will be used to sense only temperature, and 2 channels will be used to sense strain for all 12 battery cells.

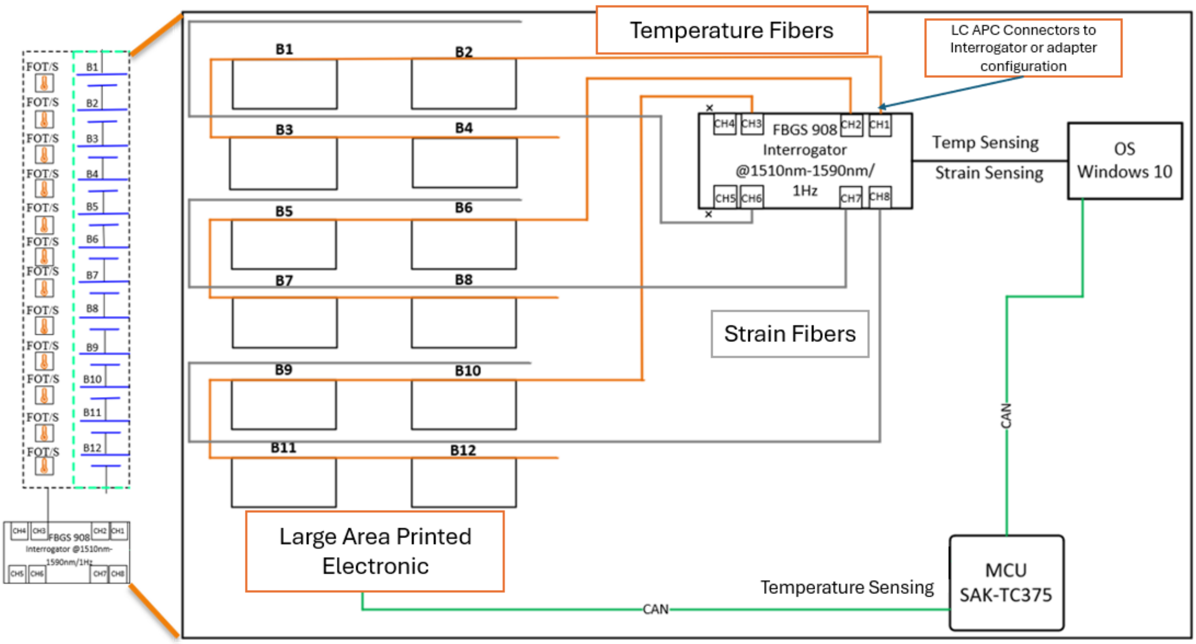


Figure 37: Temperature and Strain Sensing Layout of Fibre and Large Area Electronic Foil alongside/concurrent with Communication Interfaces

The LAE foil will be used in a similar manner. The sensed temperature data will be forwarded to the local measurement PC and the data will be recalibrated. After recalibration the temperature data will be sent on the CAN-Bus either with the same USB-CAN adapter or an additional one. This is still an open question up to now. Because all measurement points are read out sequentially on the LAE, the cyclization time will be slightly higher than the Optical Measurement Technique (approx. 3000 ms). For both sensor integrations appropriate CAN .dbc files will be provided for frictionless integration on the receiver site.

2.3.2.3 Alternative Sensor-Interfaces / EIS Sensor

Advanced SoX calculations based on EIS require very accurate cell voltage and current measurements, both in amplitude and phase for frequencies from 0Hz (DC) to a few kHz is essential. There are different ways to implement this, e.g. with a central excitation stimulus and current measurement and cell-based voltage measurement or on module level, where the excitation and current monitoring is done inside each module and the cell voltage is still measured individually, or even a cell based stimulus and current and voltage monitoring can be done.

There are different advantages and disadvantages of these concepts mainly related to synchronization precision and measurement accuracy needs. A centralized current measurement solution has the advantage that almost any current load can be used and all cells will see the same current at the same time.

NXP-AT/NXP-NED have started to develop a full chipset to support an EIS measurement solution with central excitation and current measurement and a fully synchronized high precision, long term stable cell voltage measurement system. Main focus is on the development of a novel communication Internet Protocol (IP) and synchronization algorithm which allows a high precision and high-resolution phase measurement at frequencies from DC to a few kHz.

To be able to measure all cell voltages simultaneously a quite sophisticated synchronization technology needs to be introduced. In our proposal the synchronization of all the measurement devices is done through a central 'pacemaker' integrated in the communications gateway that connects the local daisy chain with a standardized microcontroller interface. This timing reference allows to synchronize all local clock sources in the distributed network and also allows to compensate any delays introduced through the communication links e.g. repeaters in the daisy chains used between cell modules.

The challenge increases with higher measurement frequencies, if the impedance shall be measured accurately at 1 to 3kHz not only the amplitude measurement needs to be accurate but also the phase between the voltage and current needs to be measured very accurately in a sub-degree range. As the voltage measurement is done individually on cell level on different modules, the timing of the measurement must be perfectly synchronized with very high precision in a ns range. The first prototypes of the new chipset featuring the new synchronization will be available mid of 2025.

The following picture shows an example for a BMS architecture using the synchronized EIS solution:

- The Sync Gateway is providing the timing reference
- Inside the BCCs (Battery Cell Controllers) and the BJB (Battery Junction Box) the local oscillators are calibrated to the synchronization information provided by the Sync Gateway and local delays caused by message forwarding are eliminated

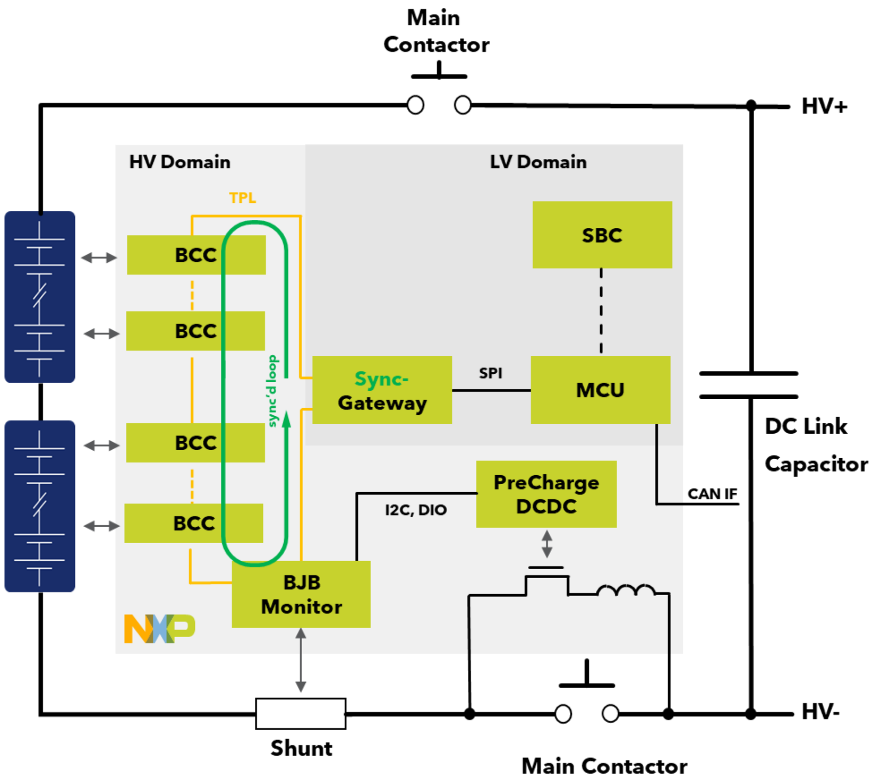


Figure 38 Synchronized BMS Architecture.

For a single cell measurement solution the voltage and current measurements as well as temperature sensing can be combined in a monolithic device even including a simple local excitation. The phase control between voltage and current measurement is no longer critical either as both instances can use the same integrated clock source. It is defined that this approach will be used in jointly developed battery module, the single cell EIS solution (DNB1168 'Linx') combines a classical cell voltage monitoring and balancing function as well as all prerequisites to do a cell-based EIS measurement.

Interfaces for new sensor concept:

Today most of the BMS applications are using resistive temperature and pressure sensors which can be connected to either the battery cell controller modules inside the HV domain or directly to battery management unit in the low voltage domain. In any case wires are needed and in most of the cases also special precaution for galvanic isolation and short circuit protection. The sensors are usually connected to A2D (Analog to Digital) frontends and required some calibration and diagnostic infrastructure. Although well-established these approaches are heavily challenged and there is the question if smart wireless solutions can be a suitable alternative:

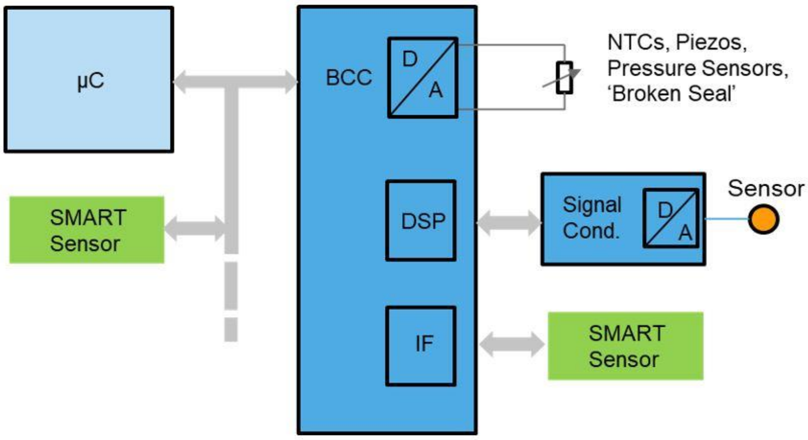


Figure 39: SMART contactless Sensor interfaces in BMS.

In a first study contactless temperature and pressure sensing methodologies using Radio Frequency Identification (RFID) or Near Field Communication (NFC) technologies are investigated, which allow to enable sensor readouts w/o the need for cables or special isolation needs. A comparison of different RFID solutions has shown that simple 13.56 MHz RFID sensors can do the job, distances of up to 20mm can be bridged, thus this would also allow communication through non-conducting HV isolation barriers. But the performance will be strongly dependent on the environment and surface materials and the required reader infrastructure is quite costly. It requires board space for the Reader IC and the required power supply components, the antennas need at least 2x3cm of area either with an air coil or a flex Printed Circuit Board (PCB), both with connectors to the cell controller PCB.
The following picture shows the setup used in NXP's lab for distance and power figure investigations, the NCF3320 is an automotive NFC reader like it is used e.g. in access systems in door handles or in the centre dashboard for identification of mobile devices, the NCF3310 is a RFID device which has an integrated A2D and an Inter-Integrated Circuit (I2C) interface which allows to connect an external sensor.

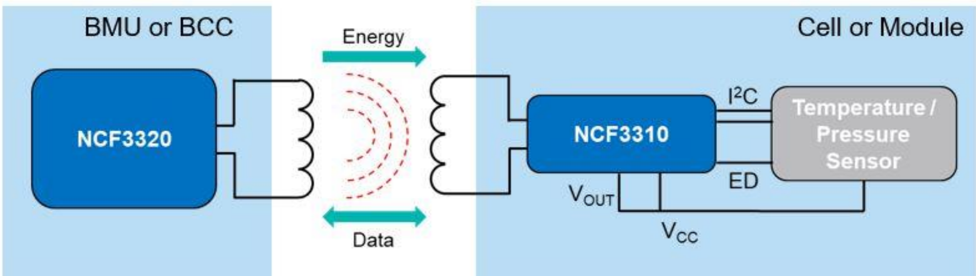


Figure 40: Layout of RFID based Sensors.

The lab bench show that despite optimizations of the transmit power and the antenna efficiency the readers are quite power consuming. Even lower power mode the drivers need to provide ~100mA of antenna current. Authentication protocols can take up to 200 ms so the energy required for a single temperature measurement will be too high. Fast authentication sequences can be used to reduce this almost by a factor of 10 but the remaining energy demand is still extremely high for a single sensor.
Sharing the reader antenna for several RFID sensors would be possible, we have seen that 4-6 sensors can share one reader antenna, but it increases the complexity of the antenna designs and if there is not possibility to switch the antenna loops on and off there is again an increase of power. Also, from a BOM perspective and the fact that next to the reader IC additional passive components and coils are needed is not attractive or suited to replace the cheap conventional wire-based sensors as used in today's solutions. Taking all this into account, an integration of RFID-based wireless sensor will not pay off in cost and performance. Investigations will be stopped in this stage, a further integration into the demo is not planned.

3 Results & Discussion

Based on the agreed requirements, a specific concept for the battery module was established, focusing on mechanical design and thermal systems. The design procedure involved three main steps: mechanical design, thermal interfaces, and electrical components integration and wiring harness. The report primarily addresses the mechanical design and thermal system, detailing the mechanical components needed for the assembly of the battery module from design to integration. It highlights the final version of the battery module and covers the main modifications made during the design steps, providing justifications and 3D representations. Additionally, the report outlines the design steps for a suitable thermal management system, including calculations for dissipated power and evaluations of heat transfer within the battery module, which serve as a baseline for assessing the cooling system's performance. For the assembly of the two battery module prototypes in Task 3.3, AIT's design process aimed to achieve a fault-tolerant battery module, necessitating a transition from design scenario one to scenario two. UL contributed preliminary estimates of power loss at maximum expected currents for the purchased cells, based on manufacturer specifications and initial electrochemical impedance spectroscopy measurements. NXP-AT investigated alternative sensor interfaces for wireless sensors, concluding that they offer no cost or performance advantages over conventional wired sensors. They also began developing a new EIS BMS chipset, with essential IP for synchronization of voltage, current, and phase measurements already implemented, and first prototypes expected in 2025. AVL-AT focused on innovative sensor integration for accurate temperature and battery swelling measurements, providing numerous design requirements, new approaches for sensor integration, and conducting reference measurements in climate chambers. They realized a sensor concept with over one hundred sensing points for spatially resolved multiparameter monitoring. All partners were involved in defining the requirements, ensuring a comprehensive and collaborative approach. The project is progressing well, with the design complete, bill of materials finalized, and components in the delivery phase.

4 Conclusion and Recommendation

In conclusion, the development and design of the battery module have successfully met the agreed requirements, focusing on mechanical and thermal systems. The design process, which included mechanical design, thermal interfaces, and electrical components integration, has been thoroughly documented. Key modifications and justifications were provided, along with 3D representations, to ensure clarity and transparency. The thermal management system was developed through detailed calculations of dissipated power and heat transfer, forming the basis for evaluating the cooling system's performance. Contributions from various partners were instrumental in achieving these results. AIT's focus on fault-tolerant design, UL's power loss estimates, NXP-AT's sensor interface investigations, and AVL-AT's innovative sensor integration have all played crucial roles. The project has progressed well, with the design phase completed, the bill of materials finalized, and components in the delivery phase.

For future projects, it is recommended to provide a detailed requirement list for mechanical, electrical, and thermal specifications at the start of the project. This will help streamline the design process and avoid potential misunderstandings. Additionally, ensuring clear communication and definitions among all partners can prevent confusion, as seen with the term 'sensor' in the early project phase. Minor adjustments may be necessary during the final assembly, but the overall design is robust and ready for implementation. Continued collaboration and clear communication will be key to the project's ongoing success and the realization of its innovative goals.

5 Deviations from Annex 1

For the battery module design with innovative sensor concept the original plan [8] was to use an already existing design for a battery module (from the COBRA project) ready for adaption according to the requirements of NEXTBMS. But it turned out, that the battery module design from the COBRA project, encountered dimensional discrepancies following the selection of prismatic NMC cells in NEXTBMS.

Therefore, the integration of new sensor measurement solutions and especially the new cell dimensions required significant design revisions, making it necessary to develop a new battery module design. The need for a thorough alignment of design requirements resulted in a robust prototype module design, offering sensor solutions adapted and tested on dummy cells, and necessary adjustments to cell spacers incorporated swiftly into the overall design. This deviation does not affect the progress of the project itself, as the assembly of the two battery module prototypes will continue as originally planned.

6 References

[1] Deliverable D2.1 (Characterisation test results of physics-based cell models), https://nextbms.eu/wp-content/uploads/sites/14/2024/03/NEXTBMS_D2.1_Characterisation-test-results-of-physics-based-cell-models_2024.02.29_V2.1-PUB2CZ.pdf

[2] Pandit, Jaideep & Thompson, Megan & Ekkad, Srinath & Huxtable, Scott. (2014). Effect of pin fin to channel height ratio and pin fin geometry on heat transfer performance for flow in rectangular channels. International Journal of Heat and Mass Transfer. 77. 359–368. 10.1016/j.ijheatmasstransfer.2014.05.030.

[3] Incropera, Frank P.; DeWitt, David P. (2007). Fundamentals of Heat and Mass Transfer (6th ed.). Hoboken: Wiley. ISBN 978-0-471-45728-2.

[4] R.H.S. Winterton. Where did the Dittus and Boelter equation come from?, International Journal of Heat and Mass Transfer, Volume 41, Issues 4–5, 1998, Pages 809-810, ISSN 0017-9310, https://doi.org/10.1016/S0017-9310(97)00177-4.

[5] https://www.alutronic.de/en/products/kuehlsysteme/pk-721-300-al-d24v/

[6] https://www.fiberoptics4sale.com/blogs/archive-posts/95046406-what-is-fiber-bragg-grating

[7] Grosch, J. et al. (2015). Device Optimization and Application Study of low cost Printed Temperature Sensor for mobile and stationary battery based Energy Storage Systems. 10.1109/SEGE.2015.7324599.

[8] Grant Agreement 101103898 - NEXTBMS, 15/03/2023.

7 Acknowledgement

7.1 The consortium

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Project partners:

#	Partner short name	Partner Full Name
1	AIT	AIT Austrian Institute of Technology GmbH
2	TNO	Nederlandse organisatie foor toegepast natuurwetenschappelijk onderzoek TNO
3	UL	Univerza v Ljubljani
4	VUB	Vrije Universiteit Brussel
5	UNR	Uniresearch BV
6	AVL	AVL List GmbH
7	AVL-SFR	AVL Software and Functions GmbH
8	AVL-TR	AVL Arastirma ve Muhendislik Sanayi ve Ticaret Limited Sirketi
9	BOSCH	Robert Bosch GmbH
10	NXP-AT	NXP Semiconductors Austria GmbH & Co KG
10.1	NXP-NED	NXP Semiconductors Netherlands BV
11	EDF	Electricite de France
12	TOFAS	TOFAS Turk Otomobil Fabrikasi Anonim Sirketi

7.2 Disclaimer/ Acknowledgment

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101103898. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

8 Appendix A

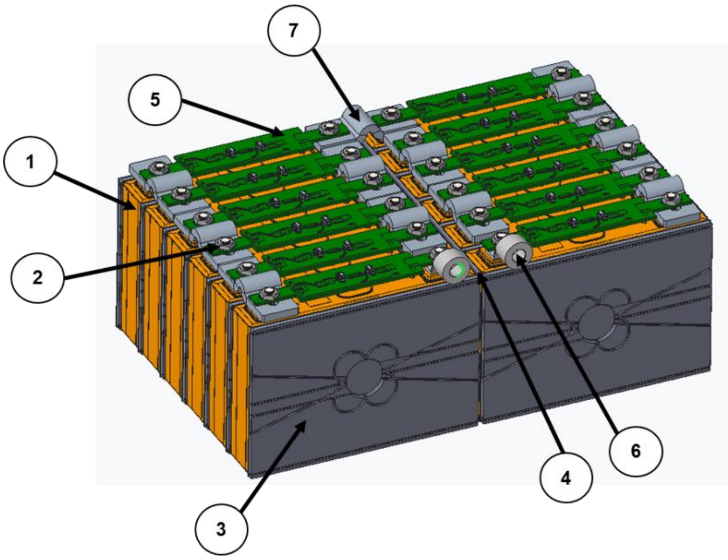
8.1 Requirement list

Category	Text	State	Comments	Requriement Reference
Heading	Introduction			
Heading	Purpose: Requirment document for the nextBMS Module Design related to T3.1	NA		
Heading	Scope	NA		
Heading	Definition and Abbreviation	NA		
Comment	Specifying requirements needs a special meaning of the following words: SHALL:This word, or the terms "REQUIRED" or "SHALL", means that the text describes an absolute requirement (shall be used for Health and Safety critical items). SHALL NOT:This phrase, or the term „SHALL NOT", means that the text describes an absolute prohibition. SHOULD:This word or the adjective "RECOMMENDED" in the text means that the requirement described has lower priority than the requirement described with "SHALL". SHOULD NOT:This phrase, or the phrases "NOT RECOMMENDED" means that the described behavior shall be avoided, but with lower priority than described with "SHALL NOT". MAY:This word, or the adjective „OPTIONAL", means that an item is truly optional. No test will check requirements described with this words. These words are the tool for the author to weight the importance of a requirement. Nevertheless the system / component shall fulfill all requirements listed in this document at the end of a development phase except requirements described with "MAY". It is not recommended to use these key-words for comments or respectively for rationales of requirements in order to avoid confusion. All requirements shall be testable clearly.			
Comment	State of Requirements: All requirements in this document are classified with individual states. These states describe the maturity of the requirements. The following states with the individual meanings are valid and shall be taken into consideration by the supplier accordingly: State: Meaning of State: New: Content of requirement may change without notice. Requirement is not to be taken into consideration for review / realization by stakeholder/supplier. In Work: Requirement under AVL internal review process. Requirement is not to be taken into consideration for review / realization by stakeholder/supplier. Requirement my be comented by stakeholder/supplier. Review: AVL internal review process completed. Requirement is ready for review process with stakeholder/supplier. Official feedback is expected from stakeholder/supplier. Approved: Requirement is accepted by stakeholder/supplier for realization. Requirement shall not change without according notification/change process.			
Heading	References	NA		
Heading	Contacts	NA		
Heading	Revision History	NA		
Comment	Version: V0.1 Revision: Initial requirement document for AVL-internal alignment Publisher/Date: 08.04.2024	NA		
Heading	Module Overview			
Heading	Sub Components	NA		
Requirement	Module shall have 58 Ah (at 1C Standard discharge) prismatic type cell.	Review		Cell Datasheet
Requirement	Each module shall be composed of 12S1P cell configuration to meet the HV Battery system.	Approved		
Requirement	Module hardware shall implement the following sub-systems (but may not be limited to only these): • Cell voltage acquisition circuits • Temperature Sensor acquisition circuits • Charge balancing circuits • Isolated Communication circuits • Diagnostic/safety circuits	Review		
Heading	Interfaces	NA		
Heading	Module-to-Cell Thermal Interface	NA		
Heading	Module-to-Cell Electrical Interface	NA		
Requirement	There shall be detachable bolt connection with M6 studs type of connection between the cells of module.	Approved		
Requirement	Module Main + & - terminal busbar are connected with Lugs for electrical interface to the battery pack.	Approved		
Heading	Module-to-Cell Mechanical Interface	Approved		
Requirement	There shall be compression pad between module end plate and cell stack.	Approved		
Requirement	Plastic part next to end plates locates cell stacks to housing and aligns bus bar assembles.	Approved		
Heading	Assembly	NA		
Requirement	Cell-to-Cell connection shall be achieved with Busbars	Approved		
Requirement	There shall be compression pads between each of cells	Approved		
Requirement	Module compression pad materials shall be specified	In Work		
Requirement	Cells series connection shall be provided with Busbars considering continuous charging current with 1.2 C-rate to ensure suitable wire sizing	Approved		
Requirement	Connection between cells shall be bolt connection with M6 studs	Approved		
Requirement	Current shall be transmitted outside with cables with M12 cable lugs	Approved		
Requirement	There shall be grounding connection to outside of module	In Work		
Heading	Component Performance and Targets			
Heading	Environmental Requirements	NA		
Requirement	Module operating ambient temperature range shall be between 0 °C to 45 °C.	Approved		
Heading	Power Requirements	NA		
Requirement	Power dissipation in module for continuous charging 66.84 W	Approved		
Requirement	Power dissipation in module for fast charging (3C for 10 seconds) 417.84 W	Approved		
Heading	Functional Requirements			
Heading	General Requirements	NA		
Heading	Communication	NA		

Requirement	Module's MCUs shall be shielded.	Approved	
Requirement	There shall be CAN Communication on Module	In Work	
Requirement	The voltages of every module's cell shall be available over a private CAN bus	In Work	
Requirement	All temperature measurements which are measured inside of module shall be available over a private CAN bus	In Work	
Requirement	There shall be LAN Interface on Module	In Work	
Requirement	Fiber optical sensor data shall be available over a private LAN interface	In Work	
Heading	Balancing	NA	
Requirement	Module shall contain CMB balancing circuitry	Approved	
Requirement	There shall be temperature sensors on the board to continuously monitor the temperature of the board near balancing resistors.	In Work	
Heading	Measurement	NA	
Heading	Voltage Measurement	NA	
Requirement	Module shall have electrical interface to MCU for continually monitoring all cell voltages individually during operation.	In Work	
Heading	Temperature Measurement	NA	
Requirement	Module shall have electrical interface to MCU for continually monitoring cell's temperature	In Work	
Requirement	There shall be up to 8 fiber channels with up to 40 sensings point on 1 fiber possible	Approved	Fiber Optic
Heading	EIS Measurement	NA	
Requirement	There shall be EIS chip to measure Impedance	In Work	
Heading	Current Measurement		
Requirement	There shall be current sensor to monitor current with a resolution of 3 mA	Approved	Current Sensor
Requirement	Safety Requirements	In Work	
Requirement	safety circuitry shall be performed via MOSFETS.	Approved	
Requirement	A short-circuit to ground / cross-wiring of poles shall be avoided.	In Work	
Requirement	An ingress of conductive liquids or dust, that can lead to unsafe behavior, undefined conditions or fire, has to be prevented.	In Work	
Requirement	The gassing of cells/modules during a failure has to be possible at all times. The generation of overpressure by the system has to be prevented	In Work	
Requirement	If the system has to be transported via air freight, a pressure compensation has to be assured.	In Work	
Requirement	A short circuit of the cell during production shall be detected and avoided.	In Work	
Requirement	An electric arcing due to misuse / abuse during installation, service, production, disposal shall be avoided.	In Work	
Requirement	An overheating / electrical spark / fire propagation from the lithium-ion battery of fuel shall be avoided.	In Work	
Requirement	An electrical arc when connecting or disconnecting the charger cable shall be avoided.	In Work	
Heading	Mechanical and Geometrical Requirements		
Heading	Material Requirements	NA	
Requirement	Module housing material will be Aluminum	Approved	
Heading	Mechanical Requirements	NA	
Requirement	MCU shall be integrated into Module.	In Work	
Requirement	BMS unit dimension shall fit into "L=TBDmm -/+ TBDmm, W=TBDmm, H=TBDmm -/+ TBDmm"	In Work	
Requirement	BMS shall be integrated into Module.	In Work	
Requirement	EE Box shall be integrated into Module.	In Work	
Requirement	There shall be wiring and harness on module	Approved	
Requirement	There shall be external measurement device (OF interrogator) connected with fibers	Approved	interrogator device
Heading	Geometrical Requirements	NA	
Heading	Thermal Requirements		
Heading	Thermal Interface	NA	
Requirement	There shall be heatsink plates on module to optimize heat dissipation	Approved	
Requirement	The module shall allow to connect a cooling plate at the bottom surface.	Approved	
Requirement	Module shall have an external fan to reduce module internal temperatures.	Approved	
Heading	Electrical and Electronic Requirements		
Heading	Voltage	NA	
Requirement	Maximum module voltage level on terminals shall be 52,2 V.	Approved	
Heading	Electric Electronic Interface	NA	
Heading	Busbar	NA	
Requirement	Busbar sizing shall be designed for corresponding current profile according to ISO 12405:2(TBC).	Approved	
Heading	LV Connector	NA	
Requirement	The connector shall contain specified number of pins.	In Work	
Heading	MCU Hardware Requirements	NA	SAK-TC375 Aurix
Requirement	Supply voltage range of MCU shall be specified.	In Work	
Requirement	The nominal operating supply voltage of MCU unit shall be specified.	In Work	
Heading	Electromagnetic Compatibility	NA	
Requirement	There shall be precautions againts electromagnetic interference on module for the MCU.	In Work	
Heading	Safety Requirements		
Comment	*Touch protection degree(IPTBD) can not be applicable on module level as Module Voltage value is lower than 60 V.*	In Work	
Heading	Labelling	NA	
Requirement	Cells and modules shall include the correct labeling for safety, warnings, and handling.	In Work	
Heading	Testing and Validation		
Heading	Warranty and Replacement Requirements		
Heading	Production, Service and Assembly Requirements		
Heading	Production	NA	
Requirement	There shall be TBD N pretension force between cells and comprassion pads	In Work	
Heading	Service	NA	
Heading	Assembly	NA	
Requirement	All parts shall be designed to avoid any sharp contactable areas which require access during assembly or service.	In Work	
Requirement	All installation processes shall be designed to be performed to minimize operator error and installation variation.	In Work	
Requirement	Components shall be free of sharp edges and burrs for safe handling.	In Work	
Heading	Recycling Requirements		
Comment	*Requirement will be added based on project aggreement*	NA	

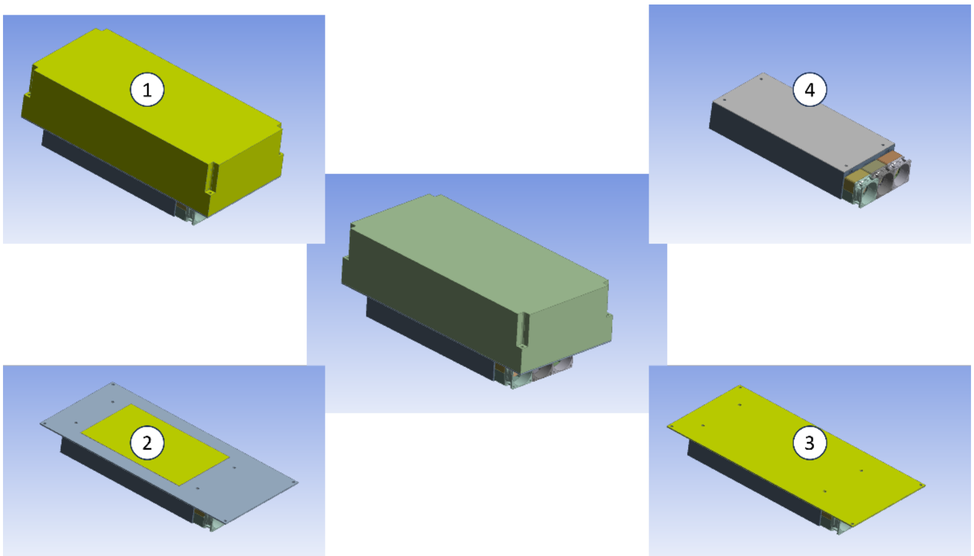
8.2 Bill of materials (BOM)

8.2.1 Cell Stack



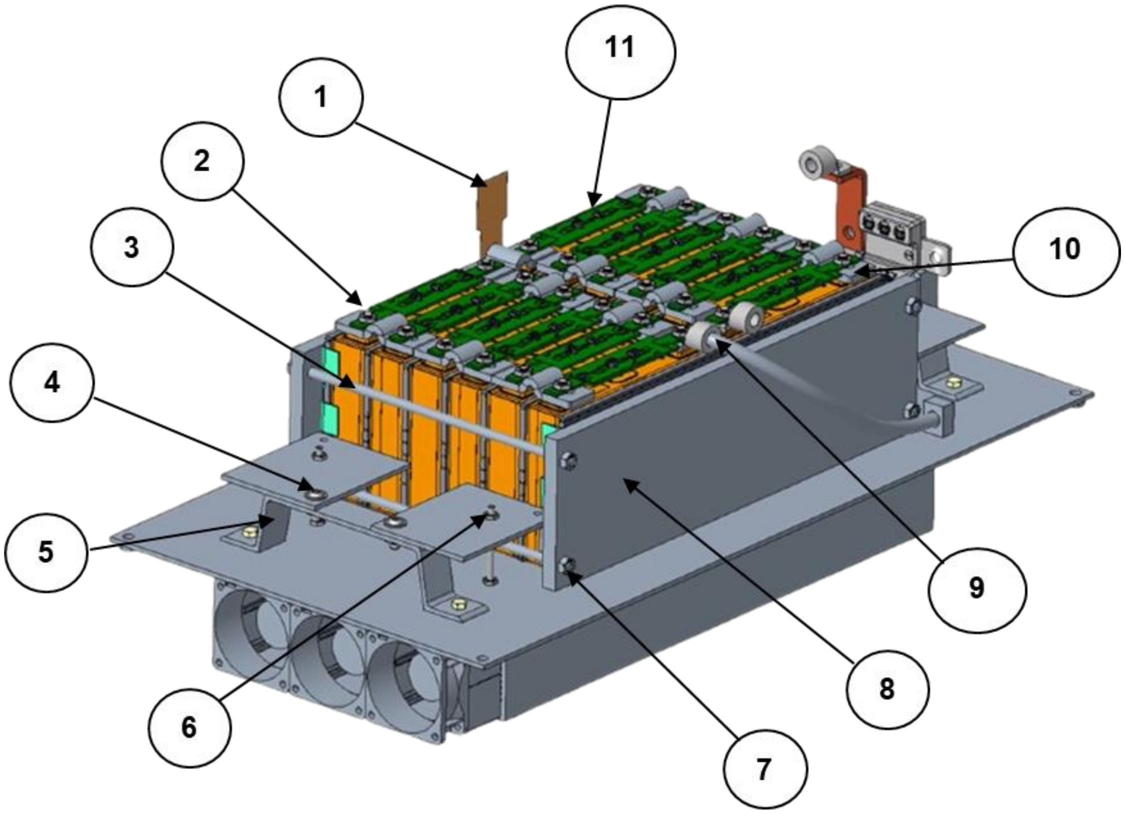
No	Part	Quantity
1	L148N58A Cells	12
2	M6 Thin Nut (ISO 4035)	24
3	Soft Compression Pads added between cells	14
4	Middle-pressure plate	1
5	CMB (Cell Monitoring and Balancing)	12
6	Cable lug	2
7	Busbar	11

8.2.2 Housing and Chassis



No	Part	Quantity
1	Hood	1
2	Thermal pad	1
3	Baseplate	1
4	Heat Sink System	1

8.2.3 Side Holders and Base Plate



No	Part	Quantity
1	Foil	1
2	M6 Thin Nut (ISO 4035)	24
3	M6 Bar	4
4	Hex Socket M6x16	4
5	Side Holder	2
6	M4 Nut	4
7	M6 Hex Nut	4
8	Module Bracket	2
9	35x6 Cable Lug Bossard	2
10	24x5 Busbar	15
11	CMB	12

9 Appendix B - Quality Assurance Review Form

The following questions should be answered by all reviewers (WP Leader, reviewer, Project Coordinator) as part of the Quality Assurance procedure. Questions answered with NO should be motivated. The deliverable author will update the draft based on the comments. When all reviewers have answered all questions with YES, only then can the Deliverable be submitted to the EC.

NOTE: This Quality Assurance form will be removed from Deliverables with dissemination level "Public" before publication.

Question	WP Leader	Reviewer	Reviewer	Project Coordinator
	Hansjörg Kapeller (AIT)	Igor Mele (UL)	Feye Hoekstra (TNO)	Hansjörg Kapeller (AIT)
1. Do you accept this Deliverable as it is?	Yes	Yes	Yes	Yes
2. Is the Deliverable complete? - **All required chapters?** - **Use of relevant templates?**	Yes	Yes	Yes	Yes
3. Does the Deliverable correspond to the DoA? - **All relevant actions preformed and reported?**	Yes	Yes	Yes	Yes
4. Is the Deliverable in line with the PILATUS objectives? - **WP objectives** - **Task Objectives**	Yes	Yes	Yes	Yes
5. Is the technical quality sufficient? - **Inputs and assumptions correct/clear?** - **Data, calculations, and motivations correct/clear?** - **Outputs and conclusions correct/clear?**	Yes	Yes	Yes	Yes
6. Is created and potential IP identified and are protection measures in place?	Yes	Yes	Yes	Yes
7. Is the Risk Procedure followed and reported?	Yes	Yes	Yes	Yes
8. Is the reporting quality sufficient? - **Clear language** - **Clear argumentation** - **Consistency** - **Structure**	Yes	Yes	Yes	Yes