Delivering the 3b generation of LNMO cells for the xEV market of 2025 and beyond

Report on pilot line manufacturing process and parameters for prototype cells

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Written By	Meirong Li (CCI), David Dirnbauer (AIT), Roberto Simmarano (SCP)	
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Project Abstract

3beLiEVe aims to strengthen the position of the European battery and automotive industry in the future xEV market by delivering the next generation of battery cells, designed and made in Europe, for the electrified vehicles market of 2025 and beyond. The project activities are focused on three domains:

- Development of automotive battery cells that are highly performant (high energy density, fast charge capability, long cycle life) and free of critical raw materials such as cobalt and natural graphite;
- Development and integration of sensors into and onto the cells to enable smart, adaptive operating strategies and advanced diagnostics in order to extend the useful life of the battery in first and second life applications and improve safety;
- A comprehensive manufacturing approach that is designed from the outset for a circular economy and industrial volumes. This encompasses green manufacturing processes for cell, module and pack, as well as recyclability assessment of the components, and a target lifecycle cost of 90 €/kWh at scale.

The project will deliver two 12kWh-demonstrator battery packs at TRL6 and MRL8. These aim at demonstrating the 3beLiEVe technology performance for applications in light duty (i.e. passenger cars, freight vehicles) and commercial vehicles (i.e. city buses and trucks) in fully electric/plug-in hybrid (BEV/PHEV) configurations.

The strong and complementary consortium of 21 partners from 10 different European countries representing industrial companies, SMEs, RTOs and academia is coordinated by AIT Austrian Institute of Technology. 3beLiEVe is scheduled to run from January 1st, 2020 to June 30th, 2023, for a total duration of 42 months and has received funding from the European Union's H2020 research and innovation programme under Grant Agreement no. 875033. A full list of partners and funding can be found at: https://cordis.europa.eu/project/id/875033.

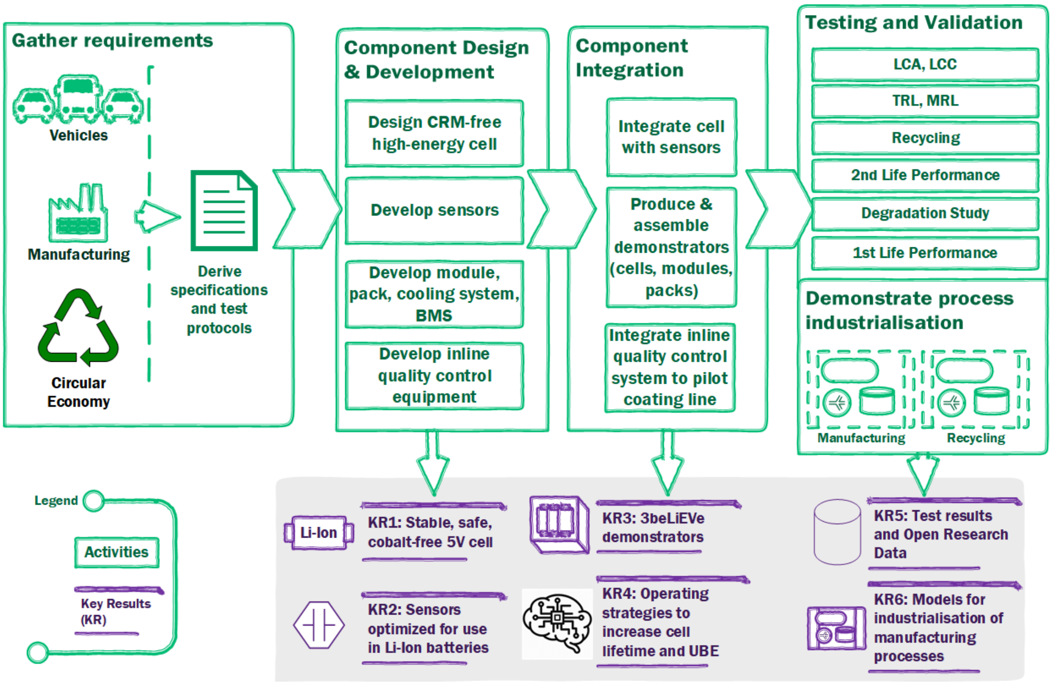

Figure 1: Overview of major 3beLiEVe project steps

Executive Summary

To extend the useful life of the battery in first and second life applications and to improve safety, the 3beLiEVe project explores the use of sensors inside and on the cell to enable smart, adaptive operating strategies and advanced diagnostics.

This deliverable is the outcome of project task *T3.3 Prototyping of the pilot cells with sensors*. It describes the manufacturing process of the 3beLiEVe pilot pouch cells, which includes the fabrication parameters of the cell components, especially the electrodes, along with a review of manufacturing-parameter-dependent energy density. It also covers the cell assembly process with respect to the inclusion of internal sensors, the focus being on aspects of mechanical integration such as sealing of internal sensors inside the cell, as well as placement and connection of sensors and sensor peripherals (such as printed circuit boards). For external sensors, similarly, sensor placement and mechanical connectivity are covered.

The operating principles of the sensors themselves are out of scope of this document. The interested reader may find supplementary information regarding sensors in the project deliverables *D4.1 Preliminary BMS design and sensor integration concept*; and *D4.2 Sensors final design*, in so far as confidentiality requirements of the project beneficiaries developing these sensors and systems allow.

Altogether, a satisfactory ability for mechanical sensor integration (including signal read-out in operando) has been demonstrated in WP3, and partially also in WP6. For the latter, some adaptations still need to be made, given that the format of the cell to be produced in WP6 differs from that employed in WP3.

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List of abbreviations

Acronym / Short Name	Meaning
BMS	Battery management system
CMC	Carboxymethyl cellulose
CMU	Cell management unit
EV	Electric vehicle
$LiFePO_4$	lithium iron phosphate
LMNO	LiNixMnyO2
MCU	Microcontroller unit
PCB	Printed circuit board
PVDF	Polyvinylidene fluoride
SBR	Styrene Butadiene Rubber
R2R	Roll-to-roll
SiC	Silicon-graphite
WP	Work package

1. Introduction

The automotive battery cell design and specifications depend primarily on the performance requirements coming from the vehicle. These include driving range, power and acceleration capability, lifetime and durability of the battery etc., which in turn are closely related to the energy of the batteries, their power capability and cycling life.

3beLiEVe aims to demonstrate generation 3b LNMO battery cells with gravimetric and volumetric energy density of 300 Wh kg^{-1} and 750 Wh L^{-1} at cell level, respectively. The selected cell chemistry to support this target consists of a high voltage spinel LNMO cathode, a high energy silicon/graphite composite anode with 10 – 20% silicon content, and a specially formulated electrolyte that facilitates the stable function of the cell components under high voltage operation. Based on a general battery fabrication process for pouch cells as presented in Figure 2, the 3beLiEVe steps to achieve the target can be summarized as follows:

i. Design and screening of battery active materials to determine and select the best-performing ones, and establishment of the primary processing parameters of these materials at laboratory scale;
ii. Upscaling the processing parameters of the selected materials, determining the fabrication parameters of the electrodes at pilot production scale;
iii. Design of the components and architecture of the pilot-scale cell, determination of the manufacturing parameters;
iv. Cell and subcomponent assembly. In the case of 3beLiEVe, the internal/extremal sensor assembly are one of the points of focus. This deliverable focuses on the fabrication parameters of the electrodes, and description of the pilot line manufacturing process of the battery cell including sensors.

Pilot-scale cell fabrication takes place in two stages in the 3beLiEVe project: first as scale-up (as a next step up from laboratory scale) on the pilot research line at AIT Austrian Institute of Technology in WP3. Once viable manufacturing parameters have been established, these are transferred to Custom Cells Itzehoe and adapted for CCI's production equipment for the production of the final demonstrator cells in WP6. This deliverable focuses on activities in WP3, with reference to activities of WP6 where expressly noted.

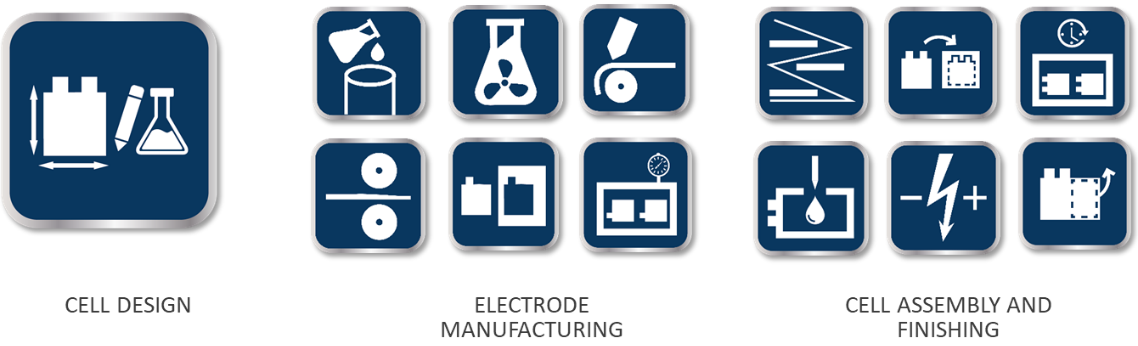

Figure 2 Graphical representation of pilot line cell manufacturing process

2. Energy density validation

The key parameters to achieve the targeted energy density of 750 Wh L^{-1} were first calculated on a theoretical basis. Based on cell calculations including the cathode and anode materials, the KPI is attainable when using cathodes with a loading of 4 mAh cm^{-2} in 77 Ah pouch cells. Applying high-loading electrodes is a well-known but also challenging path to increase the energy density. In theory, increasing the areal loading decreases the share of inactive materials, which do not directly contribute to the discharge capacity, e.g. separators and current collectors. To achieve a given cell capacity, fewer electrode layers are needed and therefore the number of inactive components is decreased.

Initial electrochemical tests with 4 $mAhcm^{-2}$ electrodes conducted in pouch cells at AIT showed that the obtained specific discharge capacity per gram LMNO at 1st cycle and 0.5C after formation was only ~65 % of the expected value. Therefore, even if that value could be improved by electrode and cell optimization, the energy density target could not be reached. It is assumed that the high areal loading leads to conductivity problems within the electrode, especially at C-rates higher than 0.2C. Therefore, the areal loading was adapted to 2.5 mAh cm^{-2} to increase the specific discharge capacity, although on a theoretical basis the energy density is reduced. First measurements showed that the reduction of areal loading results in a significantly higher specific discharge capacity. Therefore, best cell performance within the 3beLiEVe project was only achieved by reducing the areal loading.

Table 1 shows the correlation between the electrode properties and the measured energy density of the cathode including the current collector. Theoretical values, based on the expected specific discharge capacity, and the measured values in three-layer pouch cells with a standard AIT graphite anode are compared regarding the achieved energy density. Although the energy density of high-loaded cathodes is intrinsically higher on a theoretical basis, the results show that reducing the areal loading led to an increase in energy density in practice.

Table 1: Cathode energy density for 4 mAh cm^{-2} and 2.5 mAh cm^{-2} cathodes. Measured values were determined in Tri-layer pouch cells with LMNO cathodes and AIT standard graphite anodes

	Actual loading: 4 mAh cm^{-2}		**Actual loading: 2.5 mAh cm^{-2}**	
	Theoretical values	Measured values (0.5C)	Theoretical values	Measured values (0.5C)
Areal loading per side	4 mAh cm^{-2}	2,7 mAh cm^{-2}	2,5 mAh cm^{-2}	1,9 mAh cm^{-2}
Specific discharge capacity	135 mAh g^{-1} ***	90 mAh g^{-1}	135 mAh g^{-1} ***	100 mAh g^{-1}
Electrode thickness	257 µm *		173 µm *	
Energy density cathode	1479 Wh L^{-1} **	986 Wh L^{-1} **	1373 Wh L^{-1} **	1017 Wh L^{-1} **

* measured on double sided coatings with corresponding areal loading

** calculated based on 4.75 V nominal voltage

*** reversible specific discharge capacity measured in half cells

3. 3beLiEVe pilot-scale cell fabrication

3beLiEVe cell chemistry consists of a high-voltage spinel LNMO cathode, which is free of the critical raw material cobalt, a silicon/graphite composite anode able to deliver high capacity compared to state-of-the-art graphite anodes, and an electrolyte developed to enable high-voltage operation and stable cycling performance of the cell. This section presents the fabrication of the cell components including cathode and anodes.

3.1. Electrode fabrication

The production parameters for cathode and anode have been tested and optimized for the 3beLiEVe materials in different experiments. Using those parameters, the electrodes were successfully coated at AIT Austrian Institute of Technology (AIT) and Custom Cells Itzehoe (CCI). The mechanical properties were suitable for a R2R manufacturing process and the subsequent assembly process. The electrochemical properties were tested at AIT in three-layer to seven-layer pouch cells, resulting in 0.3 Ah to 0.85 Ah. The materials were mixed using a PRIMIX planetary mixer and coated on a COATEMA R2R pilot line coating facility. The electrodes were compressed using a SAUERESSIG pilot scale calender. In accordance with chapter 2, the stated properties refer to 2.5 mAh cm^{-2} electrodes. The electrodes were prepared in three sequential steps at AIT:

- Dry mixing and wet mixing steps: Focus on mixing all electrode components to a homogenous and processable slurry;
- Coating and drying: The slurry is applied as a thin layer on the current collector and the solvent is evaporated;
- Calendaring: Reduction of the initial density to improve the electrochemical properties.

3.1.1. Cathode production

Although two different generations of LNMO by Haldor Topsoe were processed at AIT within the 3beLiEVe project, the process parameters, presented in Table 2, have not been changed for the two different materials. Areal loadings starting from 2.5 mAh cm^{-2} and going up to 4 mAh cm^{-2} were coated.

Table 2 Mixing, coating and calendaring parameters for LMNO cathodes at AIT

1 - Mixing		**2 - Coating**	
Composition	LMNO4 : C65 : PVDF 93 : 4 : 3 [wt%]	Specific settings	0,5 m min^{-1}, double sided coating
Mixing	7 mixing steps, 15 - 60 min each, 10 - 75 rpm	Dryer settings	3 units, 85°C, 105°C, 95°C
		Electrode properties	Wet thickness: 200 µm Areal loading: 2.5 mAh cm^{-2}
Rest	12 h, 10 rpm	**3 – Calendaring**	
Solid content	68 %	Initial density	2.03 g cm^{-3}
		Line load	20 ± 5 N mm^{-1}
		Final density	2.45 g cm^{-3}

Based on the input concerning electrode compositions and corresponding processing parameters, the LNMO electrode production has been further upscaled to pilot production level in CCI's facility. With a composition of active material (LNMO 4): conductive additive: binder in a ratio of 93 : 4 : 3 [wt%], a uniform electrode slurry mixture could be achieved in both 10 and 20 litre production scale. Using a slot die coating process, the slurries were successfully applied both on bare aluminium foils as well as on carbon-coated aluminium foils with an areal loading of 2.5 mAh cm^{-2}. The as-fabricated LNMO cathodes have been characterized via physical and electrochemical methods. The initial electrochemical performance of the electrodes has been demonstrated in both 1Ah and 6 Ah LNMO‖graphite cells by CCI.

3.1.2. Anode production

For anode production, two different types of active materials were provided by Vianode, namely artificial graphite and silicon-graphite composite. Both materials were processed at AIT. Table 3 lists the parameters for the Si/C Anode.

Table 3 Mixing, coating and calendaring parameters for SiC anodes at AIT

1 - Mixing		**2 - Coating**	
Composition	SiC : C65 : CMC : SBR 94 : 2 : 2 : 2 [wt%]	Specific settings	0,5 mmin^{-1}, double sided coating
Mixing	SiC, C65, CMC Solution (3%), 7 mixing steps, 15 - 60 min each, 10 - 75 rpm	Dryer settings	3 units, 55°C, 65°C, 60°C
		Electrode properties	Wet thickness: 120 µm Areal loading: 2.5 mAh cm^{-2}
Rest	12 h, 10 rpm	**3 - Calendaring**	
Mixing	SBR solution (40%) added, 30 minutes, 75 rpm	Initial density	0.77 g cm^{-3}
		Line load	30 ± 10 N mm^{-1}
Solid content	44 %	Final density	1.1 g cm^{-3}

With the aim of assisting the cell system development in WP2 and WP6, CCI has produced and delivered water-based reference graphite anodes. For the anode production upscaling, SiC materials have been delivered from Vianode to CCI facility. Along with the initial processing parameters from AIT (as presented in Table 2), the SiC anode slurry will be upscaled to a volume of several litres initially in CCI's facility. The final manufacturing details of SiC anode will be presented in the D6.1.

3.2. Pouch cell production

The pouch cell production consists of various processes as described in *D3.1 Finished design of cells with internal and external sensors*.

For the small pouch cell, pilot-scale production at AIT, prior to further processing, the electrodes were dried for 12 hours under vacuum. Different pilot-scale equipment is used in the assembly process to depict a semi-autonomous manufacturing process. These assembly steps are conducted in a dry room, where the dew point of the air is held at -55 °C. The electrodes and separators were cut to AIT pouch cell format of 7 cm x 10 cm. The cell stack was built using a single sheet stacker and the battery tabs were welded to the electrodes. The cell stack was placed into the previously deep-drawn pouch foil and sealed on three sides. Arkema electrolyte was filled into the cell and sealed afterwards under vacuum. The formation of the cells was started after one hour of wetting time. After degassing under argon and vacuum atmosphere, the cells were tested according to 3beLiEVe protocols.

Several of these manufacturing steps differ for cells with sensor integration: this is elaborated in the following section.

The final format 3beLiEVe demonstrator cells with 30 Ah capacity will be manufactured via fully automatic layer-by-layer Z-folding stacking by at CCI, followed by electrolyte filling, formation and ageing processes. More detailed information concerning the scalability of the process and the resulting output will be summarized in *D6.1 FAT report on prototyped cells*.

4. Pilot cell assembling with and without sensors

The integration of external (cf. section 4.2) and internal sensors (cf. *D3.1 Finished design of cells with internal and external sensors*) into AIT pilot line pouch cells poses a challenge to the manufacturing process. For internal sensors, apart from selecting the suitable step for the integration, the placement of the sensor should not affect the cell function, e.g. causing a short circuit due to separator damage. Furthermore, proper sealing of the pouch cell should be achieved, especially when integrating internal sensors inside the cell.

4.1. Internal sensors

First sensor integration tests were conducted on pilot scale at AIT. The aim was to prove that sensors, namely PCBs and bare optical fibres can be integrated in an industry-oriented manufacturing process. Two different components were integrated on pouch cell level. The main cell assembly steps including the sensor integration points are depicted in Figure 3.

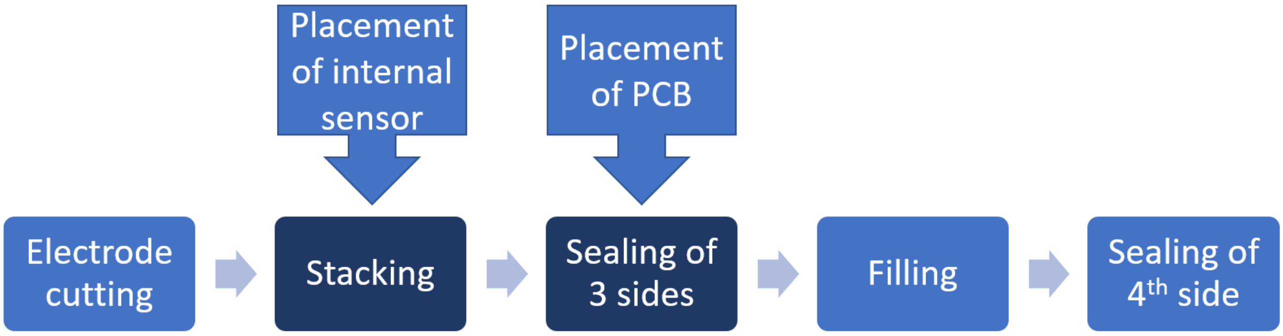

Figure 3: Cell assembly steps performed at AIT including the sensor integration steps

4.1.1. Optical fibre sensors

Optical fibres were integrated in pouch cells for optical measurements during cycling, to further investigate the connection between optical measurements and electrochemical performance. The optical fibres provided by Insplorion (INSP) use a so-called transmission mode in which the sensor (optic fibre) enters and exits the cell. Further details on the sensor design are covered in *D4.2 Sensors final design*. Damage to the fibre results in a loss of the optical signal and therefore keeping it intact throughout the whole cell assembly process was the main challenge. The primary risks were damaging the fibres during either the sealing process (thermally or mechanically) or breaking the fibres during the automated filling and degassing process.

The sensor position in the pouch cell was selected taking into consideration the assembly process employed at AIT. The main aspects are explained below and additionally depicted in Figure 4.

- “Low accessibility”: the stacking area, depicted in Figure 4, is not accessible for the operator from the back side
- “Orientation during formation”: the cell stood upright on the edge marked “orientation during formation” to ensure that all the ascending gasses are gathered in the additional pouch bag.
- “Degassing zone”: after formation the gas is removed from the additional pouch bag and the cell is automatically sealed next to the stack.

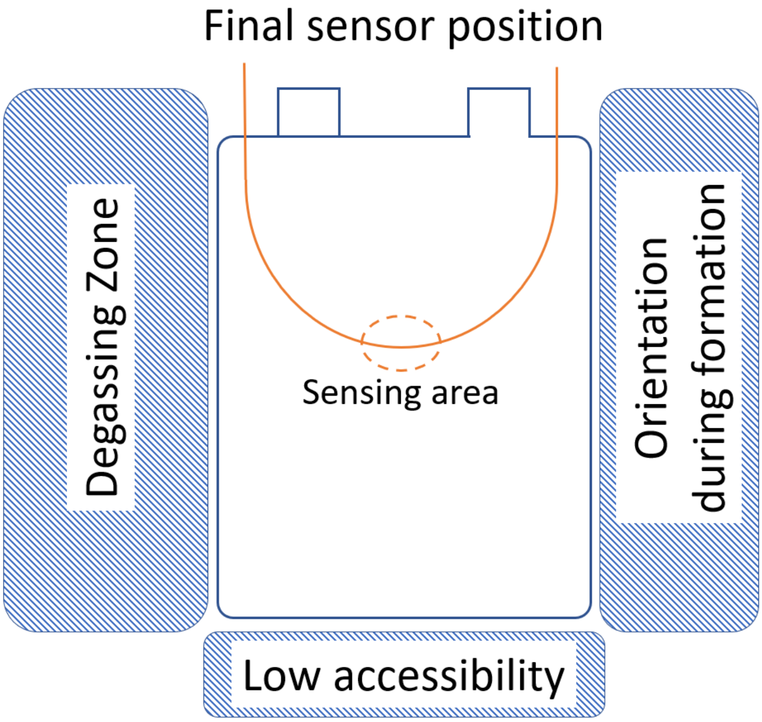

Figure 4: Final internal sensor position in AIT pouch cells

The two sensor ends were fixed next to the tabs, so that the sensor area, where the cladding of the optical fibre is removed, is in a central position within the pouch cell. The optical fibre was placed inside the stack, between the cathode and the separator. The sensor is fixed to the stack using tape. To ensure tight sealing of the sensors, additional polymer tape was added. These steps are depicted in Figure 5.

Approximately 1000 hours of optical data was gathered in four different LMNO//Graphite pouch cells at AIT using an external data logging unit to which the optical fibre was connected for light signal generation and return signal detection.

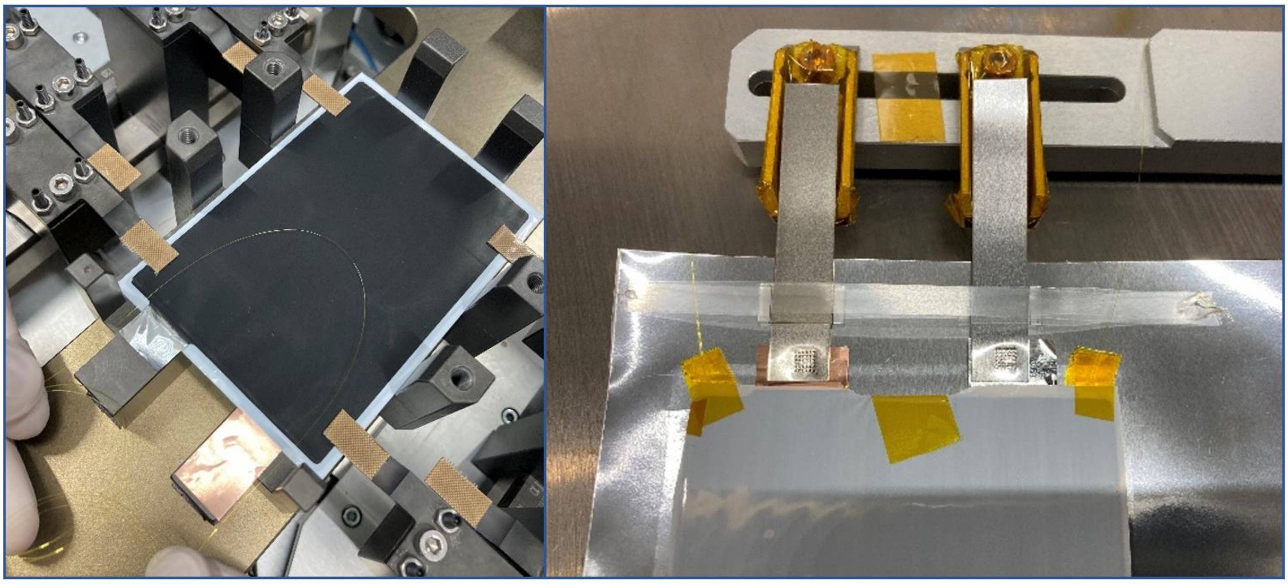

Figure 5: Placement of the optical fibre during stacking (left) and finished stack with tabs and additional polymer tape during the sealing process (right)

4.1.2. PCB integration on pilot scale

In contrast to the initial optical measurements conducted at AIT, where the fibres were connected to an external data logger, in the final cells manufactured in WP6 the optical fibres will be connected to PCBs. The PCB combines the light source and receiver on a small chip, connected via an optical fibre shaped in a small loop (cf. Figure 4, Figure 5). The PCB will be integrated into each pouch cell, welded into the pouch foil on one edge and the optical fibre is placed in-between the electrode layers.

Rigid and flexible PCBs were used for first integration tests conducted at AIT, where the necessary process parameters for successful integration were investigated. The findings are depicted in Figure 6.

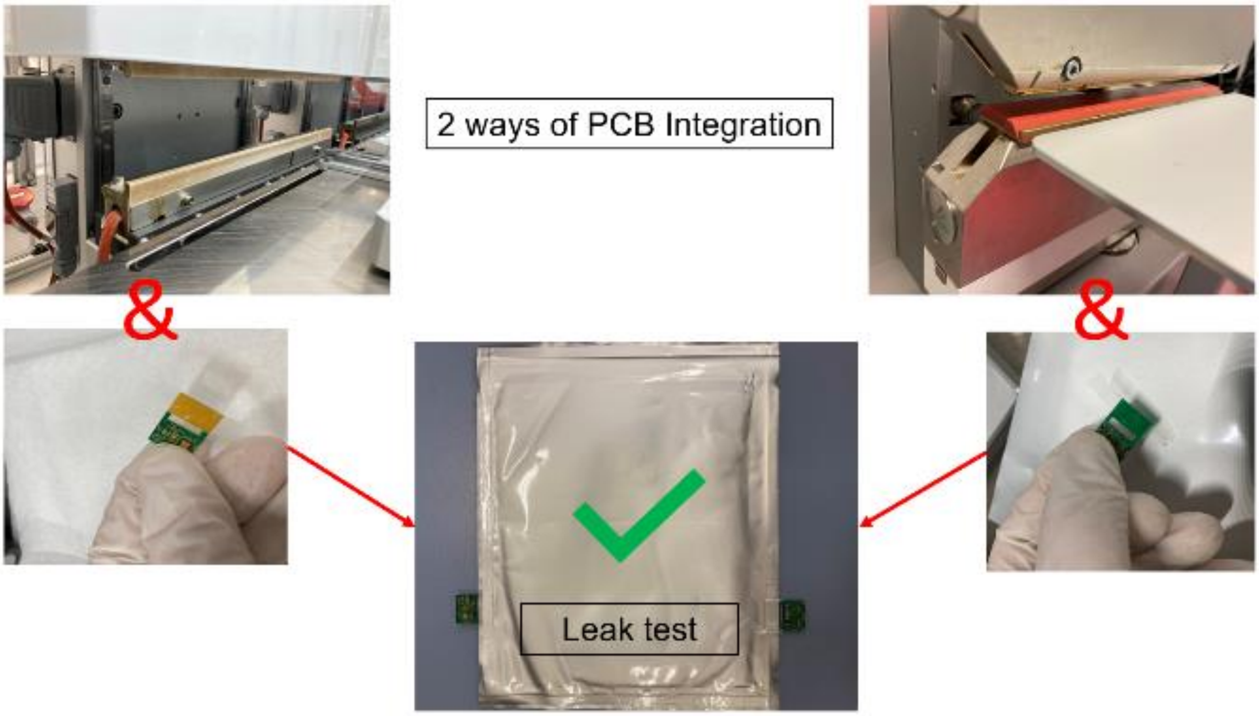

Figure 6: Two possible ways of PCB integration at AIT using different sealing equipment and PCB design. Rigid steel sealing bars combined with flexible PCB layout (left side) and flexible sealing bars with rigid PCB layout (right side)

The main challenge was to ensure a tight seal without damaging the pouch foil near the PCB. Tests with rigid PCBs show that the sealing bar properties (flexible or rigid) and the sealing force are two main factors for success. The combination of the rigid PCB with a steel sealing bar results in either damaging the pouch foil in the PCB area or in insufficient tightness next to the PCB, when the sealing force is reduced. The rigid PCBs can only be integrated using at least one flexible sealing bar, e.g. made of silicone. Well-functioning pouch cells with integrated PCBs were successfully built at AIT and are depicted in Figure 7.

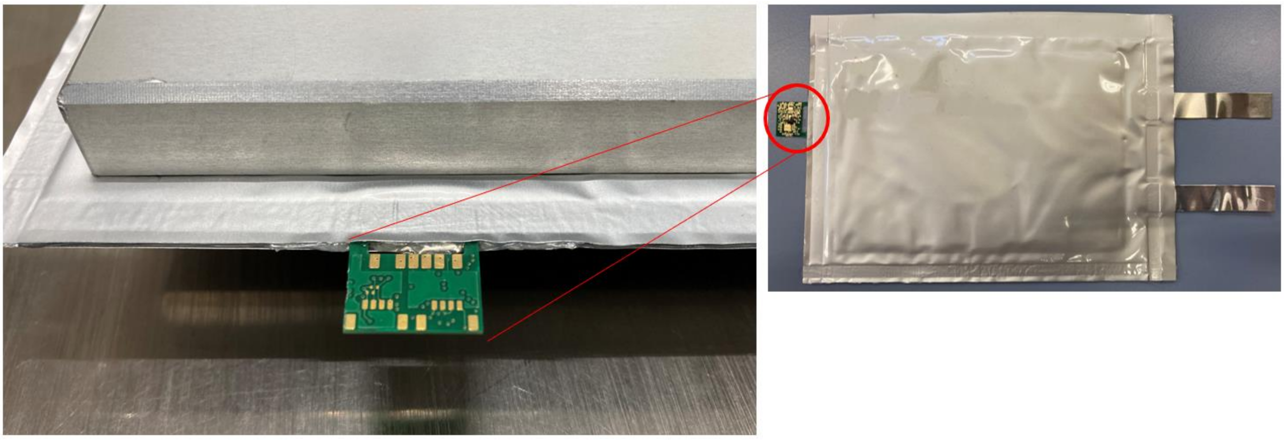

Figure 7: Fully operational cell with integrated PCB manufactured at AIT

These findings were communicated to WP4 and WP6 and provided the basis for finalizing the PCB design and the integration process in WP6.

4.1.3. Internal sensors in WP6

The development roadmap for the cell with internal sensors in WP6 consists of the initial sealing and leakage tests, which have met with success in the current preliminary stage, the initial electrochemical tests and data acquisition at cell level, and manufacturing of the quality-assured cells for the module assembly.

For the sensor integration in the final format of the 3beLiEVe cell with its counter-tab design, the position of sensors and glass fibres has raised various considerations. There are two main challenges concerning the internal sensor integration into the final 3beLiEVe cells: first, the integration of the glass fibre should not adversely affect the electrochemical nor the safety performance of the battery cells. Second, the internal sensor integration raises additional considerations regarding module/pack design due to the configurations of extra components to accommodate such integration (mainly to facilitate communication with the BMS). During the initial discussions, several strategies for the integration of glass fibres and PCBs in the cell were proposed, and these proposals were initially tested in dummy pouches and dummy cells to check the feasibility.

Graphical representations of the proposed strategies are shown in Figure 8. Figure 8a shows the “rigid-flex” PCB strategy, which is based on a design where the PCB is divided into two parts: a rigid PCB which could be placed on to tab, and a coupling PCB which is foldable and can be placed between the cells. This proposal has been declined due to the complex PCB design and the limited space in module. Other suggestions such as a “sideways PCB” (Figure 8b), based on the concept of placing the PCB on to tabs to avoid interference with the module design and benefit the cooling systems, as well as the possibility of incorporating the internal sensor’s PCB on or near the flexible circuit patch of the external sensor (cf. Figure 10), were also considered. However, difficulties were encountered in the sealing trials; a high risk of cell leakage and potential interference with electronic connections was recognized. The other proposal is placing the PCB directly next to the tab and sealing in the cell as well (Figure 8c and 8d). The initial sealing trials of the two PCBs developed in the project inside the 3beLiEVe pouch were successful. Based on the module design, the PCB with smaller size is preferred in this case (Figure 8d).

Manufacturing the 3beLiEVe format battery cells with integrated internal sensors still faces challenges due to the limitations in battery cell design itself, especially the targeted tab sizes and their positions, the low technical maturity in internal sensor integration, as well as the hitherto unknown subsequent cell performance and any reactions that may take place between the cell chemistry and the sensors. The latter question is further explored in *D3.3 Test report of influence of internal sensor on performance and degradation*.

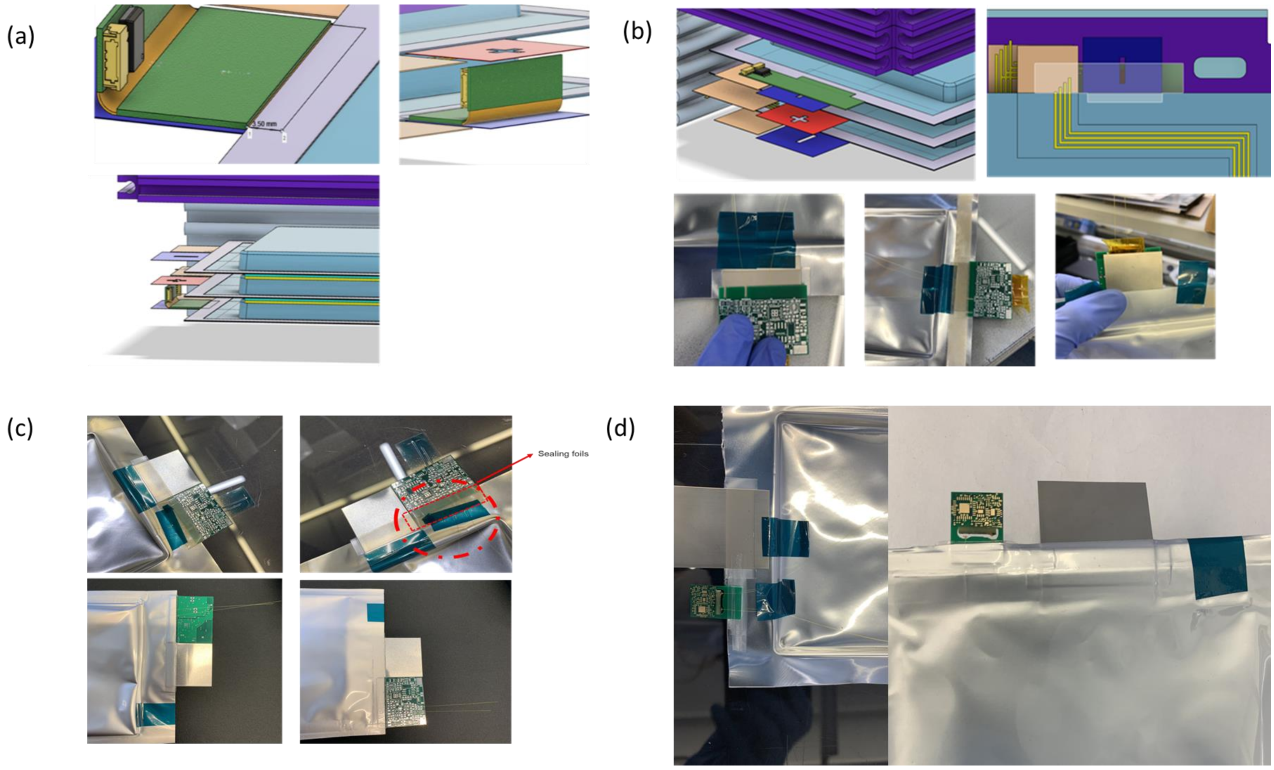

Figure 8. Proposed strategies of the internal sensor integration

4.2. External sensors

External sensors, developed by Sensichips (SCP) in WP4 and described in *D4.1 Preliminary BMS design and sensor integration concept* and *D4.2 Sensors final design*, were integrated onto pouch cells within WP3. This section covers key features of the sensors, the tests with external sensors conducted at SCP and at AIT, as well as the outlook on the following tasks.

4.2.1. Cell Management Unit (CMU) introduction

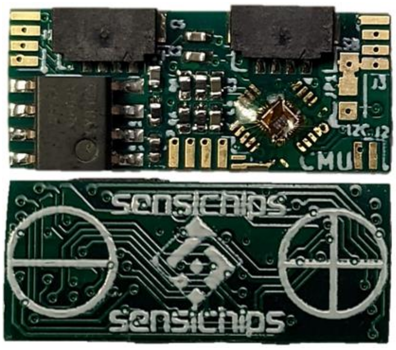

Figure 9: Close-up of the SCP CMU.

The CMU can perform multiple measurements on battery cells, super-capacitors or fuel cells while in operation. It was designed with targets of utmost miniaturization and low costs so that it can be installed on each battery cell, turning it into a smart cell.

The CMU is based on the SENSIPLUS microchip, which includes an electrochemical impedance spectrometer (EIS) with lock-in amplifier, measuring 1st, 2nd and 3rd harmonics, a potentiostat/galvanostat along with on-chip sensors for temperature, relative humidity and gassing. The anode and cathode electrodes included in the CMU kit enable a four-contact measurement of the cell internal impedance and tab temperature. With such a setup the CMU performs measurements with 150µΩ precision. Coulomb counting can be performed without a shunt resistor and can be adjusted for ageing.

An off-chip interface supports external sensors such as strain, pressure, and moisture (e.g. from electrolyte leakage or condensation). Multi-sensor measurements are cross-correlated by the SENSIPLUS Learning Machine (SLM) running on a Micro-Controller Unit (MCU) in the battery module, to stream minimal data to the BMS. The CMU is largely chemistry independent; it can be used with Li-Ion and Li-Fe-PO_4 battery packs, similarly it can be applied to 3b generation of LNMO cells, supercapacitors and fuel cell combinations.

4.2.2. CMU and external sensor integration with battery cells

Since battery cells can come in many different shapes and forms, we designed the CMU as a tiny electronics board with two wings whose length is cut to fit the specific cell geometry. The terminal tabs of the two wings are then connected to the battery cell tabs, either with soldering, screws, or pressure clips. The connection of the CMU terminal tabs to the cell tabs is critical, since it can affect measurement accuracy. The described CMU configuration allows for the versatility needed for initial experimentation with different cell types and form factors. For the final battery module design in 3beLiEVe or in volume production, the CMU should be adapted to custom-fit the specific cell geometry and to remove all extra wires.

<u>Integration at Sensichips' laboratories</u>:

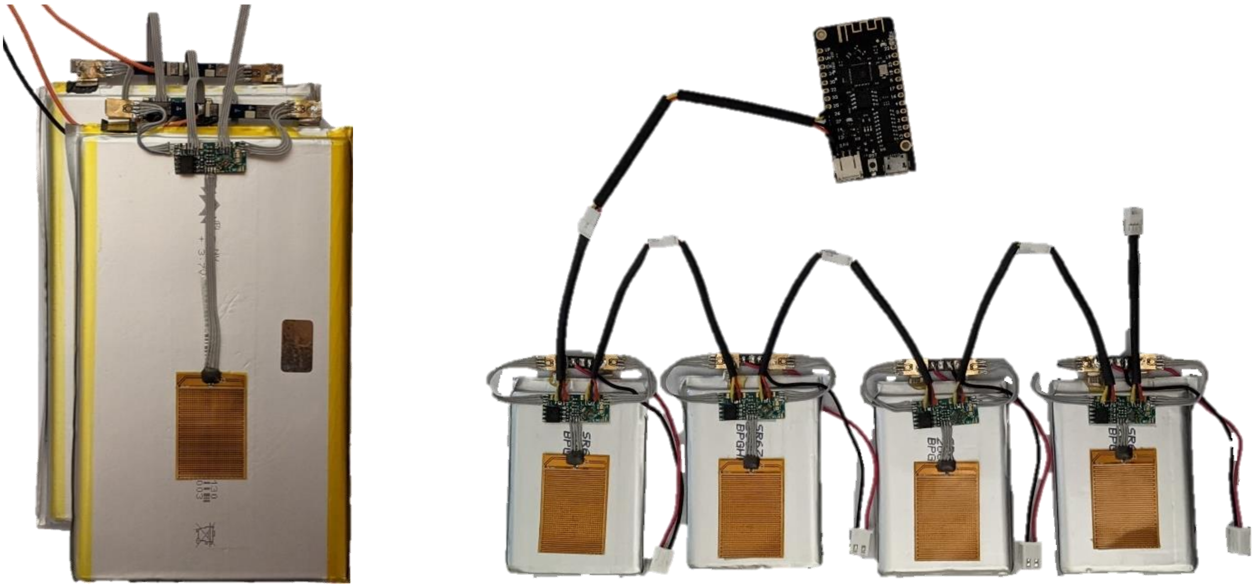

Figure 10 Left: The CMU mounted on two commercial daisy-chained 12Ah LiPO battery cells. Right: The CMU mounted on four daisy-chained 2Ah LiPO battery cells and connected to a Wireless Microcontroller that implements a distributed BMS. In these two configurations, the tabs are soldered.

At Sensichips laboratories we performed a few integration tests with different cell form factors and evaluated the impact of tab connectivity with the cell tabs on measurements. We tested with different pouches, prismatic and cylindric cell types.

Figure 11: CMU mounted on daisy-chained $LiFePO_4$ prismatic batteries.

Figure 11 shows the CMU mounted on two daisy-chained 200Ah $LiFePO_4$ prismatic batteries for industrial machines and industrial EVs. The photo shows the CMU connected with two different screw configurations.

The flexible circuit patch that can be seen glued on the centre body of the pouch cells and connected to the CMU with a four wires flat is never critical to install (Figure 10). This patch is a 3-in-1 sensor and it measures battery body temperature, swelling and potential electrolyte leakage or formation of moisture. More critical is the connectivity of the two measuring wings to the battery tabs, especially when fixed with screws or pressure clips.

Integration at AIT laboratories:

Subsequently, integration tests were performed at AIT laboratories in Vienna. These tests focused on batteries provided by project partner Custom Cells (CCI), with large capacity and having a form factor and mechanical design emulating the final 3beLiEVe project cells for automotive use with opposite side tabs.

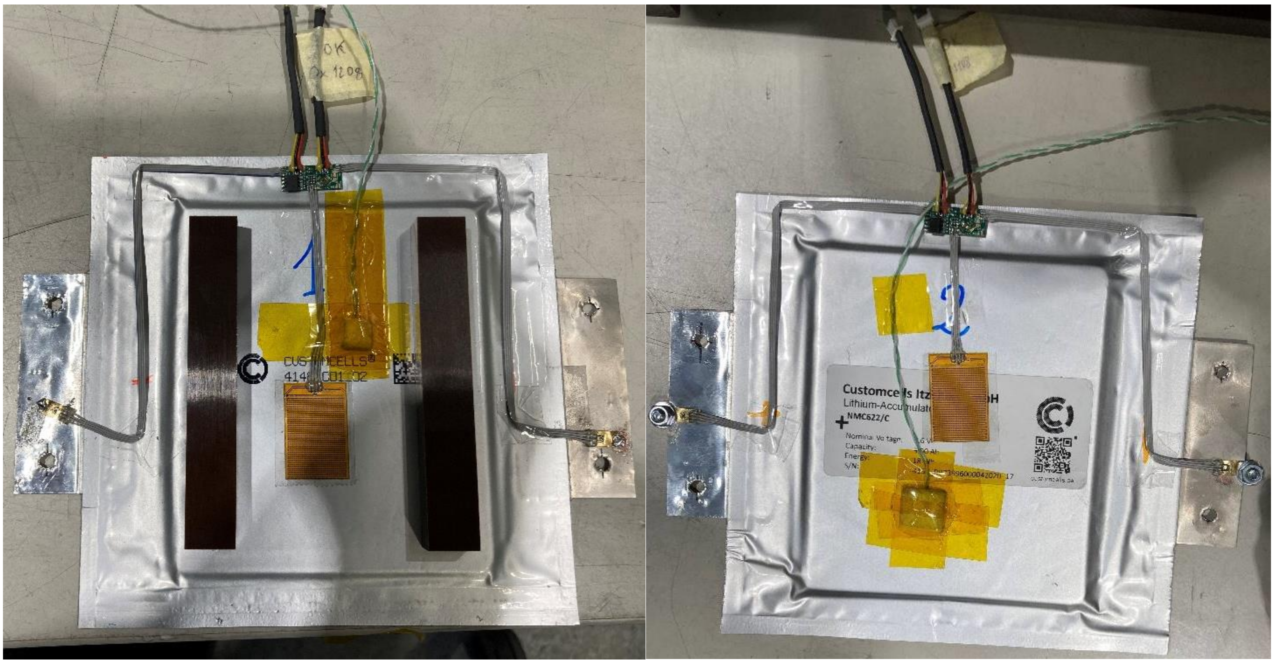

Figure 12 Left: The CMU measuring tabs are soldered with the large battery tabs, Right: The CMU measuring tabs are screwed with the battery tabs

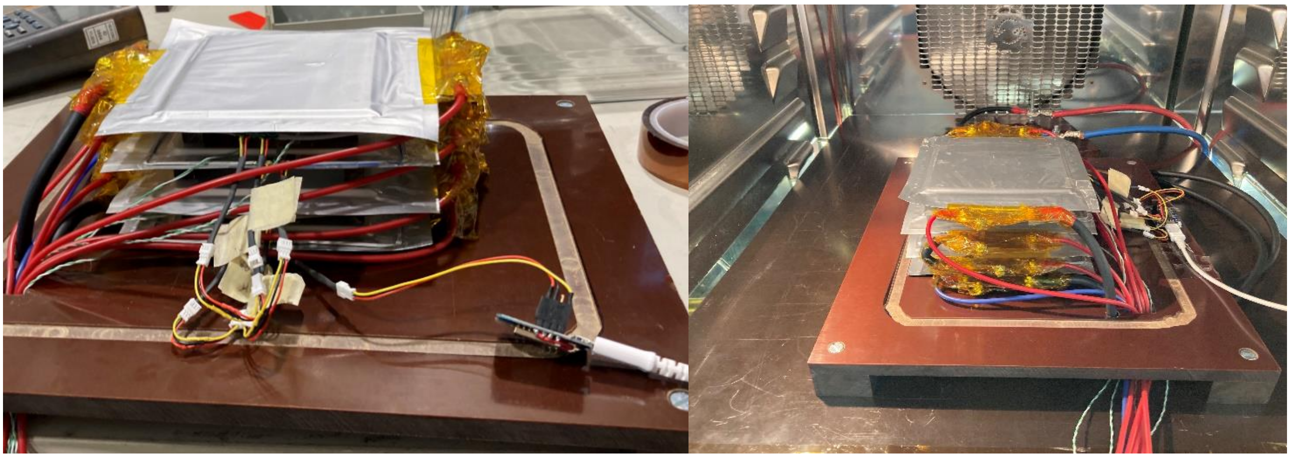

Figure 13: Emulation of a four-cell battery module; Left: A Four cells daisy chain stack of the Custom Cells integrated with the CMU; Right: The Four cells stack inserted in a controlled climate chamber for measurements

Figure 14: Four CMUs measuring battery internal resistances.

Figure 14 shows four CMUs measuring the respective battery internal resistance, with each smart cell resistance having a different colour. It can be noted that the smart cell with yellow colour measures a much higher internal resistance with respect to the other three smart cells. This can be due to either of the following three reasons:

a) The yellow cell is not screwed on properly and therefore the CMU also measures the interface parasitic impedance between CMU and cell tabs;

b) The yellow cell is more aged compared to the other three cells;

c) The yellow cell has a much higher internal resistance due to manufacturing spreads.

It was easy to confirm that the first hypothesis was true, with better tightening the screws of the yellow cell.

4.2.3. Outlook and next steps

In WP3, SCP has validated the CMU and external sensor integration with battery cells. Most of the focus was on assessing the impact of the connectivity between the CMU measurement tabs and the battery cell tabs. This is critical since it can affect measurement accuracy. Wires inside battery modules normally are solder welded, screwed or connected with pressure snaps. While solder welding is preferred from a measurement accuracy and reliability standpoint, it also makes the battery module more complex to service and disassemble. On the other hand, vibration and shock can impair connectivity based on screws or pressure snap mechanisms. The experience in this task triggered ideas to make the CMU connectivity with battery tabs more resilient also in screwed or pressure-tab-based configurations. These will be implemented in time for the final test phase of the project. The integration of the measurement patch on the battery body, the 3-in-1 sensor measuring temperature, swelling, electrolyte leakage or possible formation of moisture, doesn’t pose issues since it can be reliably glued over the polymeric/plastic enclosure of the battery.

More details with extensive CMU characterization and measurements will be reported in *D4.2 Sensors final design*.

5. Conclusions

This deliverable explained the 3beLiEVe cell manufacturing process and the steps necessary for integrating optical sensors inside pouch cells. It also gave an overview of the integration of a multi-measurand sensor system on the outside of the cell. As this deliverable involves achievements from the partners Custom Cells, Sensichips, Insplorion and AIT, the work was done in close coordination between those partners.

The electrode properties, as stated in *D3.1 Cell architecture design with internal plus external sensors*, were validated in various pouch cells and tests at AIT. The results showed that increasing the actual cathode energy density was achieved, counterintuitively, by decreasing the areal loading of the electrodes. Final key parameters for the mixing procedure, the coating step and the electrode calendaring were described.

Successful integration of internal and external sensors into and onto pilot line pouch cells was reported, overcoming challenges such as sealing tightness, sensor and PCB placement, and tab connections, while avoiding damage to the cells or the sensors.

Further information on sensors can be found in the project deliverables *D4.1 Preliminary BMS design and sensor integration concept* and *D4.2 Sensors final design*. Final 3beLiEVe-format demonstrator cells will be documented in *D6.1 FAT report on prototyped cells*.

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