Deliverable D4.5

FREE4LIB battery pack design, Battery Manufacturing, Assembly and its Validation report

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Feasible Recovery of critical raw materials through a new circular Ecosystem for a Li-Ion Battery cross-value chain in Europe

WP 4 - Scaling and validation of feasible technologies

D4.5 - FREE4LIB battery pack design, Battery Manufacturing, Assembly and its Validation report [M28]

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Versions

DATE	VERSION	AUTHOR	COMMENT
20/06/2025	1	EUT	First draft of the document
30/06/2025	2	EUT	Internal review suggestions applied
15/07/2025	3	CARTIF	Final document

Contents

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Table 1. Abbreviations and synonyms

ACRONYMS	DESCRIPTION
DfR	Design for Recycling
BMS	Battery Management System
DUT	Device Under Test
CCCV	Constant Current - Constant Voltage

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1. Introduction

This deliverable gathers the information regarding the outputs of task T4.8, providing a comprehensive explanation of the design of new batteries based on DfR guidelines. The current document focuses on the final application and requirements for the battery packs, the electrical architecture and the final design, as well as the chosen components. The required documentation for manufacturing, assembly and disposal phases, such as technical drawings, is also included in the deliverable.

The primary objective of this deliverable is to design a battery casing and its internal components using eco-design principles, including Design for Disassembly, Recycling, and Durability. Also, it is crucial to ensure mechanical compatibility, structural integrity under vibration and impact, thermal management, corrosion resistance, and compliance with electrical isolation and safety standards.

2. Application selection for F4L battery pack

In the first subtask [ST4.8.1], the application for the battery packs has been determined. This decision has been made according to the progress in WP2, regarding the previous research, the health status of the battery and the recovery process; WP3, covering at laboratory level the recycling per parts and the different applications depending on the status of the battery, and WP4, addressing the recycling per parts at a scaled level.

In the realm of transportation, a variation of applications was studied, including different kinds of electrical vehicles focusing on urban mobility, specifically two-wheelers, such as scooters, motorcycles, and bicycles. These vehicles are especially well-suited for congested city environments due to their agility, lower costs, and reduced environmental impact.

Finally, the e-bike was chosen as the use case for transport. The e-bike is cost-effective, requiring minimal initial investment and offering lower operating costs compared to larger electric vehicles. Furthermore, an old e-bike was available at **EUT**, which allowed the recycled battery to be used within a final demonstrator.

Figure 1. Images of the old e-bike available at EUT and the battery mounted.

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3. Requirements for the design of F4L battery pack

The following requirements in ST4.8.2 were defined by **IREC**, aligning with the most common specifications for an e-bike. Standard values for capacity, voltage, and power ensure compatibility with 250 W motors and typical charging systems, making the reuse of the existing battery a cost-effective and environmentally friendly choice without compromising performance.

The list of battery specifications is presented in Table 1.

Table 1. Definition of parameters and specification for the battery cells.

Parameter	Specification
Battery Capacity	10 Ah
Battery Voltage	36V
Battery Current	7.8 A
Max Power	250 W
Dimensions	39 x 7.6 x 11 cm
Weight	6 kg
Charging Voltage & Current	42V, 2A
Charge Time	4-6 hours

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4. Components and electrical architecture of F4L battery pack

In the following subtask [ST4.8.3], the electrical architecture and its design are explained in detail: the objectives of the use case and what needs to be considered for its purpose in the battery design, the selection of a battery casing, the specification of the technical characteristics of the cells, and the creation of the electrical diagram to illustrate the connection between the different components. Finally, in this section, a validation report will assess the performance, safety, and compliance, ensuring the battery pack meets all operational requirements.

4.1 Battery casing

There were two options for choosing the battery casing. In the first place, the original casing from the existing e-bike was reused to minimize material waste. This choice benefits from an already compatible design, which ensures an easy integration with the rest of the e-bike and its mounting system. The following images show how it looks in the context of the battery, the individual part, and its cross-section.

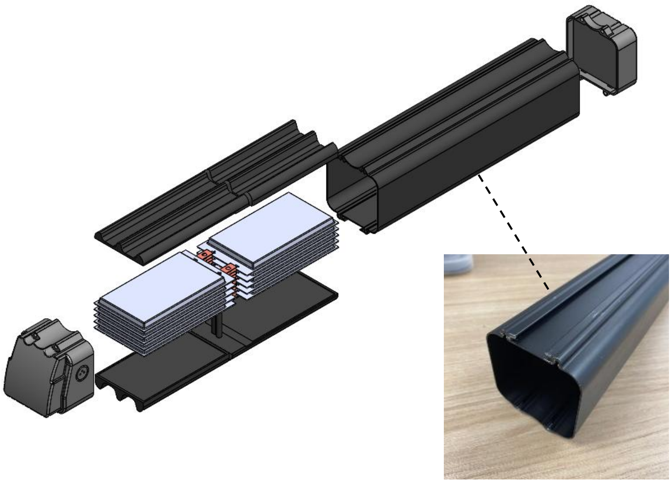

Figure 2. Image of the reused battery casing.

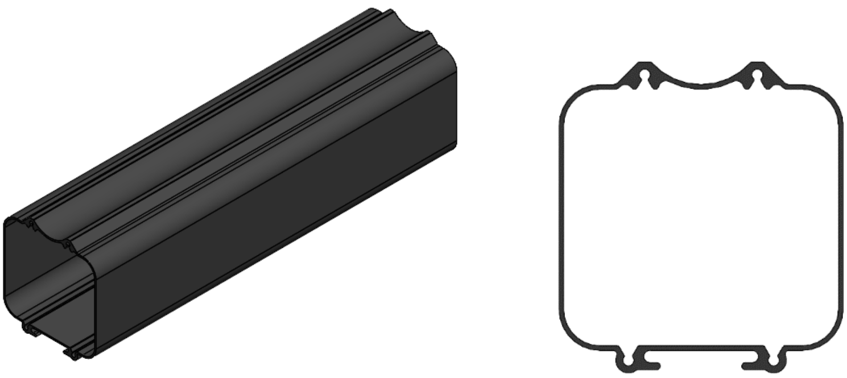

Figure 3. (Left) 3D model of the reused battery casing and (right) cross-section of the battery casing.

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In the second place, a new casing was developed using aluminium plates and profiles made from recycled aluminium. This casing offers a modular mono-material structure with easy assembly and maintenance. The following images show how it looks in the context of the battery, the individual part, and its cross-section.

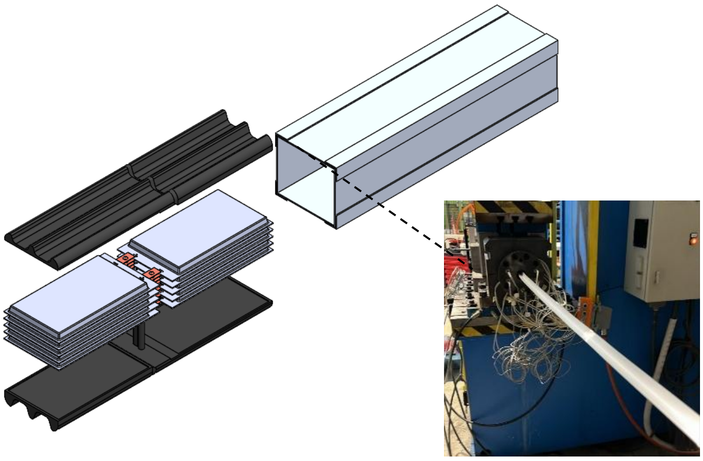

Figure 4. Image of the new design of the battery casing.

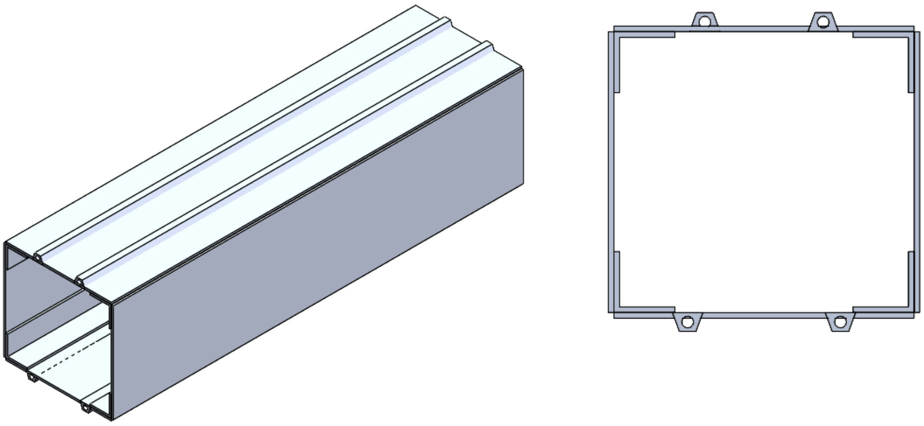

Figure 5. (Left) 3D model of the new design of the battery casing and (right) cross-section of the battery casing.

4.2 Plastic components

In the context of the battery design, plastic materials are used for support components that are also essential for housing and positioning the cells, as well as creating the connectors between them. As part of Task 4.5 of the FREE4LIB project, a comparative analysis has been conducted between plastic materials recovered in Task 3.5 from battery packs HYUNDAI KONA EV and the most common commercial plastics used in the automotive sector. The objective is to compare the project-recovered materials with these alternatives most commonly used for 3D printing, such as ABS, PLA, and ASA, which was the manufacturing processes used to produce the prototype’s plastic components.

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Three main streams of materials recovered from the battery packs were analyzed:

- PPE (from cell frames)
- PA66 and PA11 (from connectors, fittings, and tubes)
- Expanded PP (from insulation panels)

These materials were compared with ABS, PLA, and ASA based on key properties: mechanical strength, thermal resistance, impact resistance, and processability. The values for the recycled materials were taken from deliverable D3.8 of the FREE4LIB project. Reference values for virgin materials are based on bibliographic sources listed in the references section, including Harper (2002), Mark (2007), Auras et al. (2010), Jamshidian et al. (2010), Strong (2005), and Osswald & Menges (2003).

Table 2. Comparison of the properties of recovered and 3D printing plastics

Property	ABS	PLA	ASA	Recovered PPE	Recovered PA66	Recovered PP (expanded)
Tensile strength (MPa)	40-50	60	40-50	78.1	77.2	-
Flexural modulus (MPa)	2000	3000	2000	4050	5050	-
HDT (°C)	~95	60	100	122–128	233–243	-
Charpy impact (kJ/m2)	15–20	<5	20–30	9.64–34.58	6.3–32.44	-

- **Recycled PPE** offers superior thermal and mechanical performance compared to ABS and ASA, making it suitable for structural components or those requiring thermal insulation. It also exhibits higher impact resistance than the benchmark material, making it ideal for energy-absorbing applications (e.g., frames, covers). In contrast, ABS and ASA provide good processability and impact resistance but have lower thermal stability, limiting their use in high-demand thermal environments. PLA, while bio-based and mechanically sound in tension and flexion, lacks impact and heat resistance, limiting its role in functional components. Therefore, although ABS and ASA could be partial alternatives in non-critical applications, recycled PPE is technically more suitable for demanding uses.

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- **Recycled PA66 and PA11** demonstrate high rigidity, thermal resistance, and stability, outperforming ABS and ASA in mechanical demands. PA66 is ideal for technical parts, while PA11, recovered from tubing, provides chemical resistance and flexibility - properties that PLA lacks. Together, these recycled polyamides offer superior performance over commercial alternatives for structural, thermal, or chemical applications.

- **Recycled expanded PP**, obtained from battery insulation panels, cannot be reprocessed into foamed material due to its high flow and low melt strength. Although its cellular structure cannot be restored, the material can be repurposed in compounding or injection molding for non-structural applications. ABS, PLA, or ASA are not suitable substitutes in foamed applications due to their lower energy absorption capacity and closed-cell structures.

Recycled PPE, PA66, and PA11 exhibit high technical performance compared to ABS, ASA, and PLA, though they do not fully match the mechanical requirements for all applications. Their potential lies not in direct substitution, but in advanced recycling and upcycling, allowing for adaptation to new functional uses. Recycled expanded PP retains value in non-structural applications, where ABS, PLA, or ASA lack comparable properties. These results reinforce the project's strategy of promoting the reintegration of these materials through high-value circular solutions.

4.3 Cells

In this chapter the technical specifications of the cells will be given. This is an important part, since battery cells are the fundamental and unitary building blocks of any assembly of a battery system. As such, the outcome of this chapter will be the technical specifications themselves, which are essential to design, build and test the prototype, but also the inspection and data gathered during the process.

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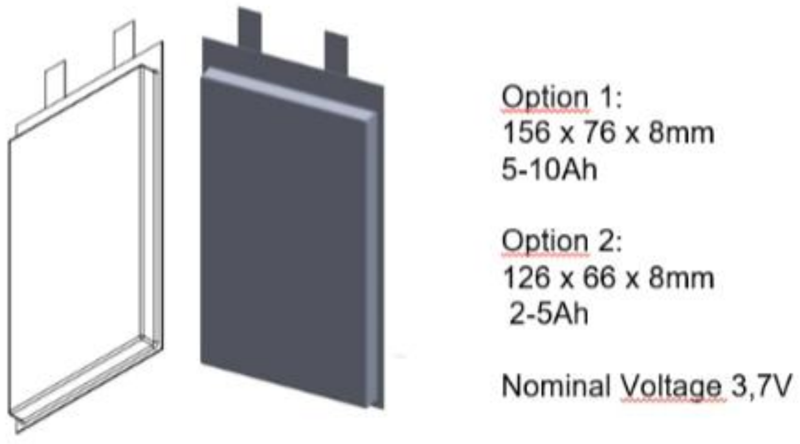

Figure 6. Sketch shared with both viable options for prototype assembly.

Figure 6 shows the two viable options from NES to manufacture cells according to the requirements. Finally, option 1 was chosen as the corresponding cells to be used within the prototype, because both the capacity and mechanical dimensions adjusted better to the requirements stipulated beforehand, during the design to fit within the metallic casing.

Table 3. Theoretical technical specifications of each individual cell.

Parameter	Specification
Cell Capacity [Ah]	6
Cell Nominal Voltage [V]	3.7
Minimum Cell Voltage [V]	2.8
Maximum Cell Voltage [V]	4.2
Maximum Cell Discharge Current [A]	3 (0.5C)
Maximum Cell Charge Current [A]	1.2 (0.2C)
Maximum Working Temperature [ºC]*	45

**A safe and conservative approach was taken to establish the temperature limit according to previous uses of cells of the same chemistry and initial behaviours at EUT.*

As a security protocol, on the arrival of any DUT (Device Under Test) at the laboratory, it is subject to an initial visual inspection with the bare eye, and a thermal inspection with the thermal infrared camera. This allows one to verify

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if cells have been damaged during the shipment, and if any hotspots are present, which could indicate internal short circuiting and thus a safety threat.

An individual inspection of each battery cell was carried out. A total of 15 cells were received, of which 5 were found to be in poor condition due to shipping damage, such as swelling or electrolyte leakage ("red" condition). Four additional cells showed visually or technically uncertain signs ("amber" condition), meaning they could be used with caution. The remaining 6 cells were in very good condition ("green" condition). In some cells voltage oscillations were measured. The battery cells were then charged to their nominal voltage (3.7 V) using a CCCV method. This approach ensured the pack would be reasonably balanced before assembly, minimizing potential risks. In any case, after assembly, a more thorough balancing process was planned. The results of visual and thermal inspections, thickness measurements, voltage behaviour while testing with the multimeter, the overall status condition and initial voltage can be seen in Table 4.

Table 4. Results of the initial visual and thermal inspections.

Status	Battery number	Thickness (mm)	Visual/Thermal Status	Finally used	Voltage (V)	Oscillation when testing voltage
	Cell 1	6,05	Too thin	No	NA	NA
	Cell 2	8,7	Patched	Yes	3,5	NA
	Cell 3	9,8	OK	Yes	3	↓
	Cell 4	10,3	Swelling	No	NA	NA
	Cell 5	8,6	Possible hole	Yes	3,51	NA
	Cell 6	9,15	Leakage	No	NA	NA
	Cell 7	8,83	Dirty	Yes	0,49	NA
	Cell 8	9,06	OK	Yes	3,56	NA
	Cell 9	9	Leakage	No	NA	NA
	Cell 10	9,05	Dirty	Yes	3,74	NA
	Cell 11	8,4	Dirty	Yes	2,13	↓↑
	Cell 12	8,82	Swelling	No	NA	NA
	Cell 13	8,95	Patched	Yes	3,59	↓↑
	Cell 14	8,88	OK	Yes	1,19	↓
	Cell 15	8,5	OK	Yes	3,57	NA

↓↑ Voltage oscillates up & down when checking with the multimeter around the specified value, which would be the average in this case.

↓ Voltage decreases when checking with the multimeter.

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Lastly, images of the physical dimensions of the cells are given in Figure 7.

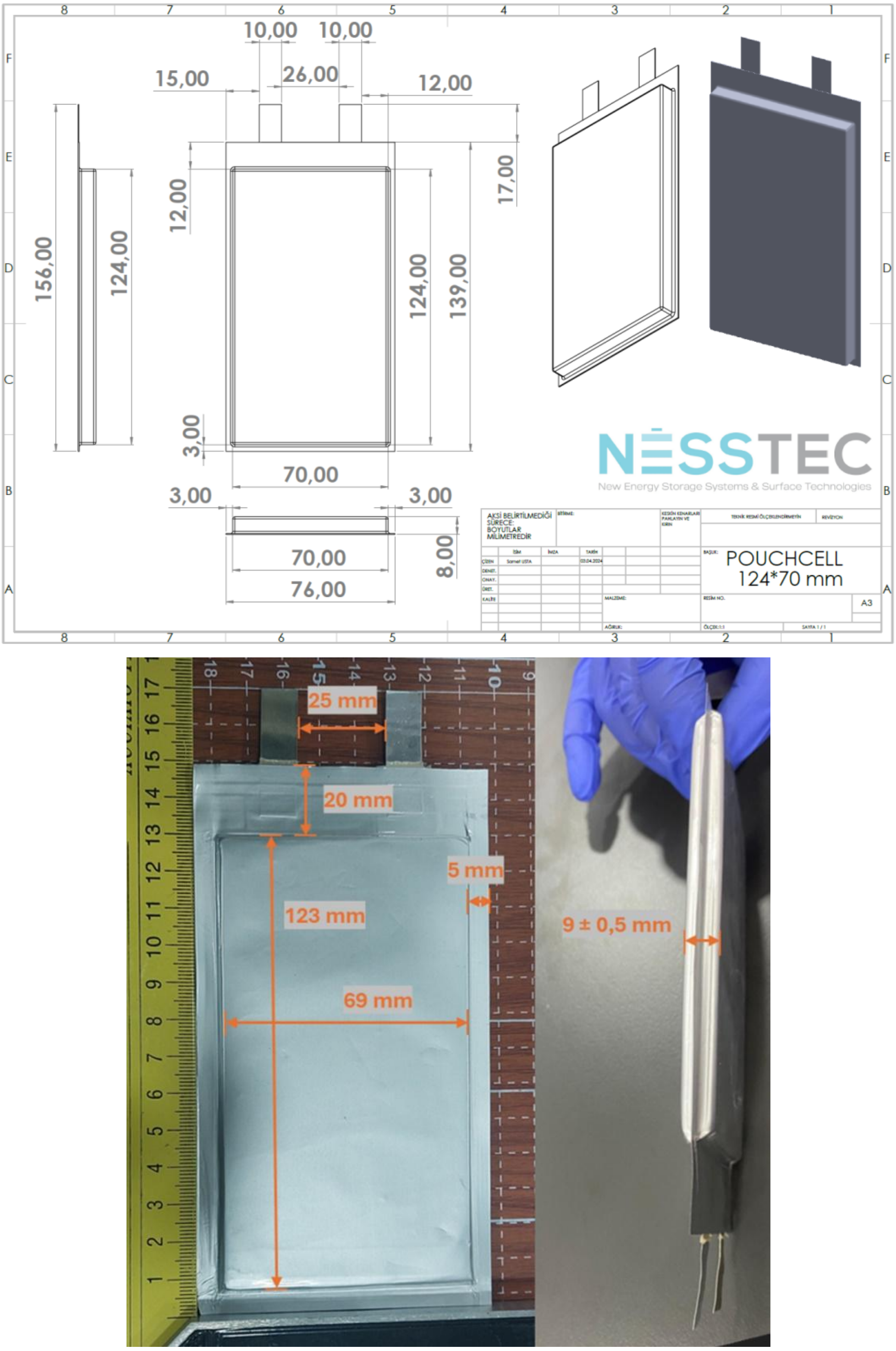

Figure 7. Images showcasing the physical dimensions of the cells.

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4.4 Electrical architecture

The design of the battery also includes careful consideration of the specifications and design of electronic circuits. The Battery Management System (BMS) is the responsible for monitoring and protecting the cells. It manages voltage, temperature, and current, ensuring safe operation and optimal performance. In the design diagram, it acts as the central hub, connecting and coordinating all electrical and thermal protection elements. The electrical diagram of the battery is shown in Figure 8.

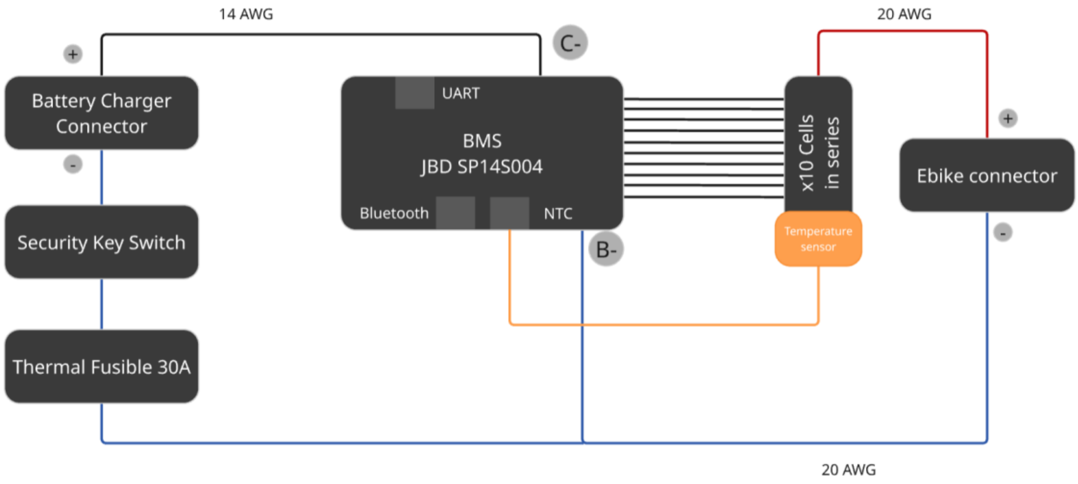

Figure 8. Electrical diagram of the battery.

A modular and stackable design has been chosen for the "contactor" components. These pieces are covered with a copper layer, allowing them to conduct electricity between the cells through direct contact with one another. The geometries have been specifically designed with a central guiding element that ensures each piece can only be positioned in the correct orientation, facilitating safe and accurate assembly.

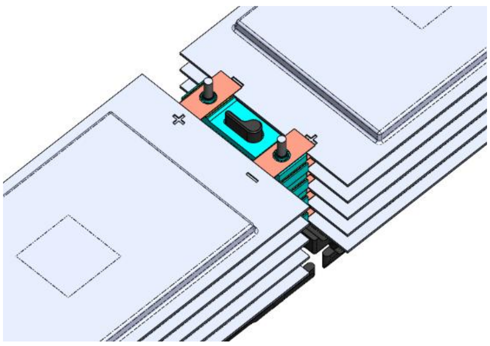

Figure 9. Stacked cells and contactors aligned with the special piece.

The contactors (blue components shown in Figure 10) are design with an interlocking mechanism which allows each piece to connect securely with the

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previous one. This geometry also serves as a protection for the threaded rod that holds them together, reducing the risk of short circuits. To prevent such incidents, an additional protective layer, such as a heat-shrinking tube, is applied around the central part of the rod, excluding the top and the bottom to allow threading.

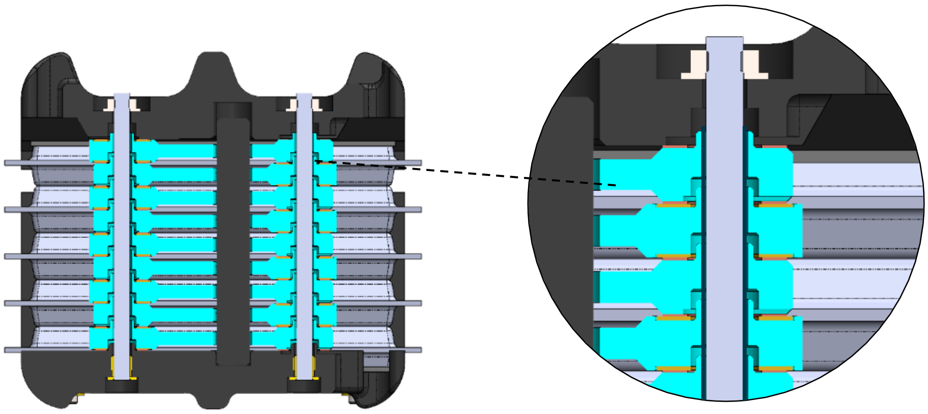

Figure 10. Cross-section of the assembly of the battery cell frames, the cells, the contactors and its joints.

5. Design of the F4L battery pack

The design of the battery pack is based on several eco-design strategies, focusing on sustainability and recyclability. The design is guided by inputs from ST4.8.1 (application), ST4.8.2 (requirements), and T5.3 (recycling guidelines). Some of the guidelines followed include the maximization of recycled material usage, design for recycling, facilitation of cell replacement, implementation of weldless connections, and minimization of disassembly time.

Throughout all design iterations, the cells are arranged in an interleaved pattern (Figure 11 and Figure 12), alternating between Position A and Position B, driven by their polarity orientation. This layout enables proper electrical alignment while maintaining a compact and balanced structure.

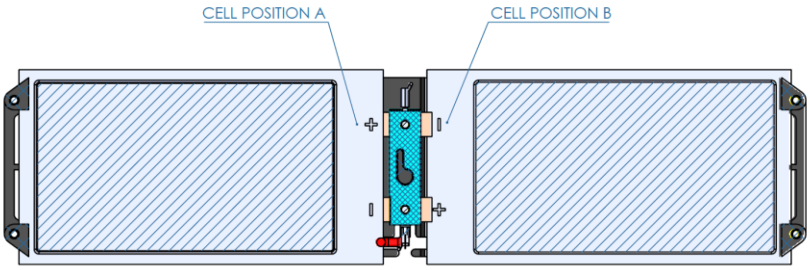

Figure 11. Cell positioning inside the battery case.

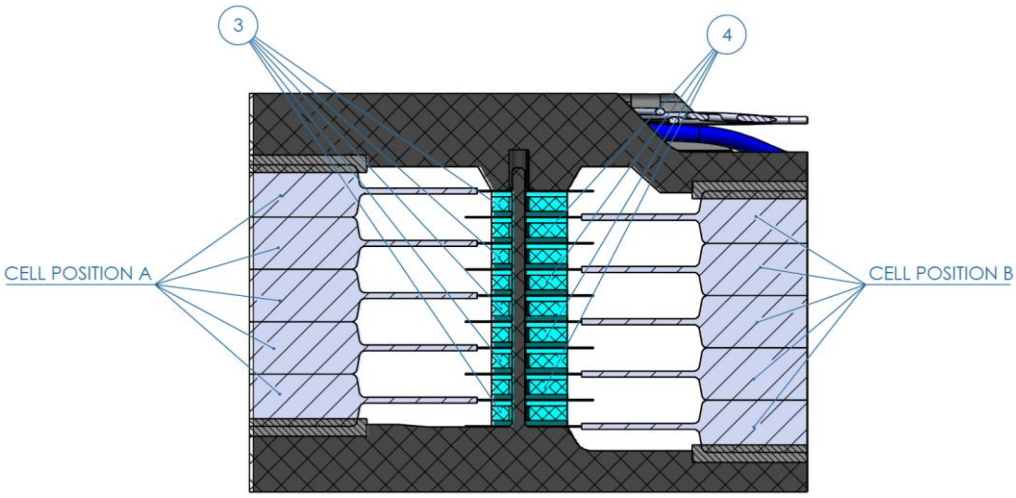

Figure 12. Cross-section of the cell and contactor positioning.

In this initial design iteration (Figure 13 and Figure 14), the battery pack is composed of two structural components: an upper and a lower frame. These parts provide support and vibration damping and ensure precise central positioning of the cells within the enclosure.

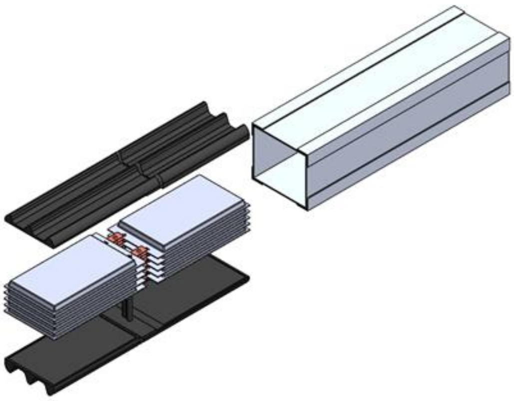

Figure 13. First design iteration of the battery design (new casing design).

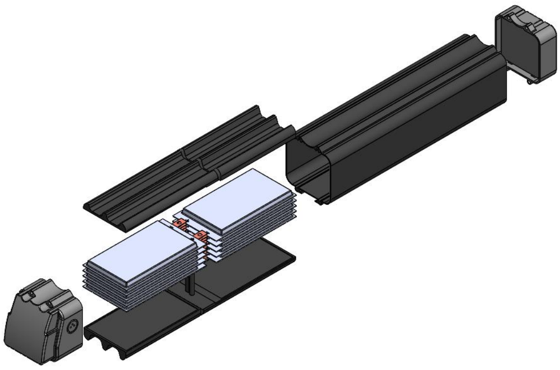

Figure 14 First design iteration of the battery design (reused casing).

In the second design iteration (Figure 15 and Figure 16), the upper and lower frames have been updated to improve structural integrity and component fixation. Both frames are now secured using lateral screws, enhancing the overall rigidity of the assembly. Additionally, two dedicated screws are included to firmly secure the battery cells and contactors in place. This version also introduces compression pads, strategically positioned to absorb shocks and

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control vibrations during operation. These compression pads can also absorb the swelling forces that cells can generate during the use.

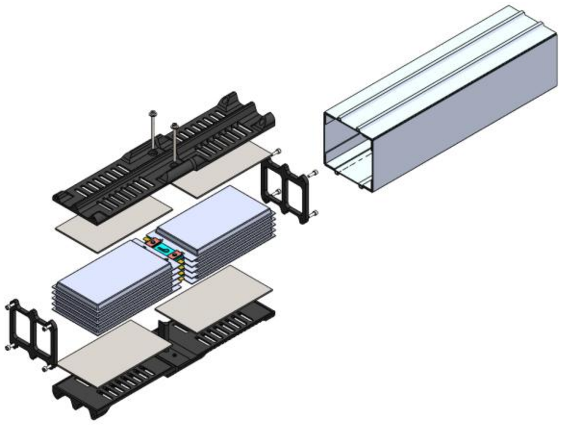

Figure 15. Second design iteration of the battery design (new casing design).

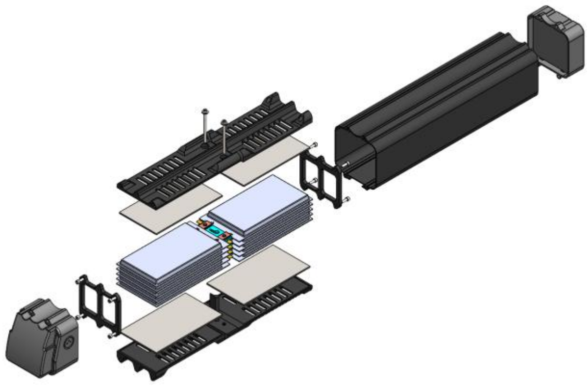

Figure 16. Second design iteration of the battery design (reused casing).

The final design is 330 mm long, 73,6 mm wide and 68,6 mm tall. In this final model the wiring is also modelled in the CAD design and the position of the BMS is shown. Subtle changes were made regarding the frame cell, which was split horizontally in two pieces, avoiding extra parts on the sides. It is fastened using screws and threaded rods, which secure the position and vibration of the cells in the battery.

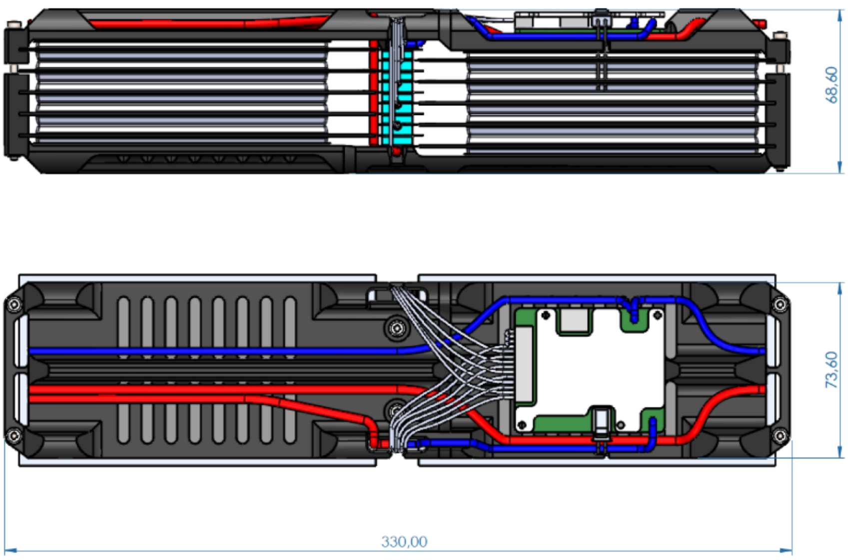

Figure 17. General dimensions of the F4L battery cell frame, including the BMS.

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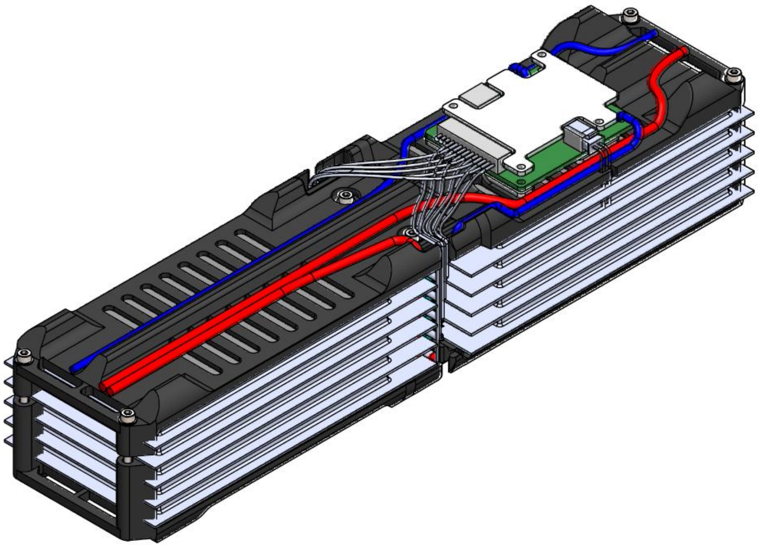

Figure 18. Isometric view of the F4L battery cell frame.

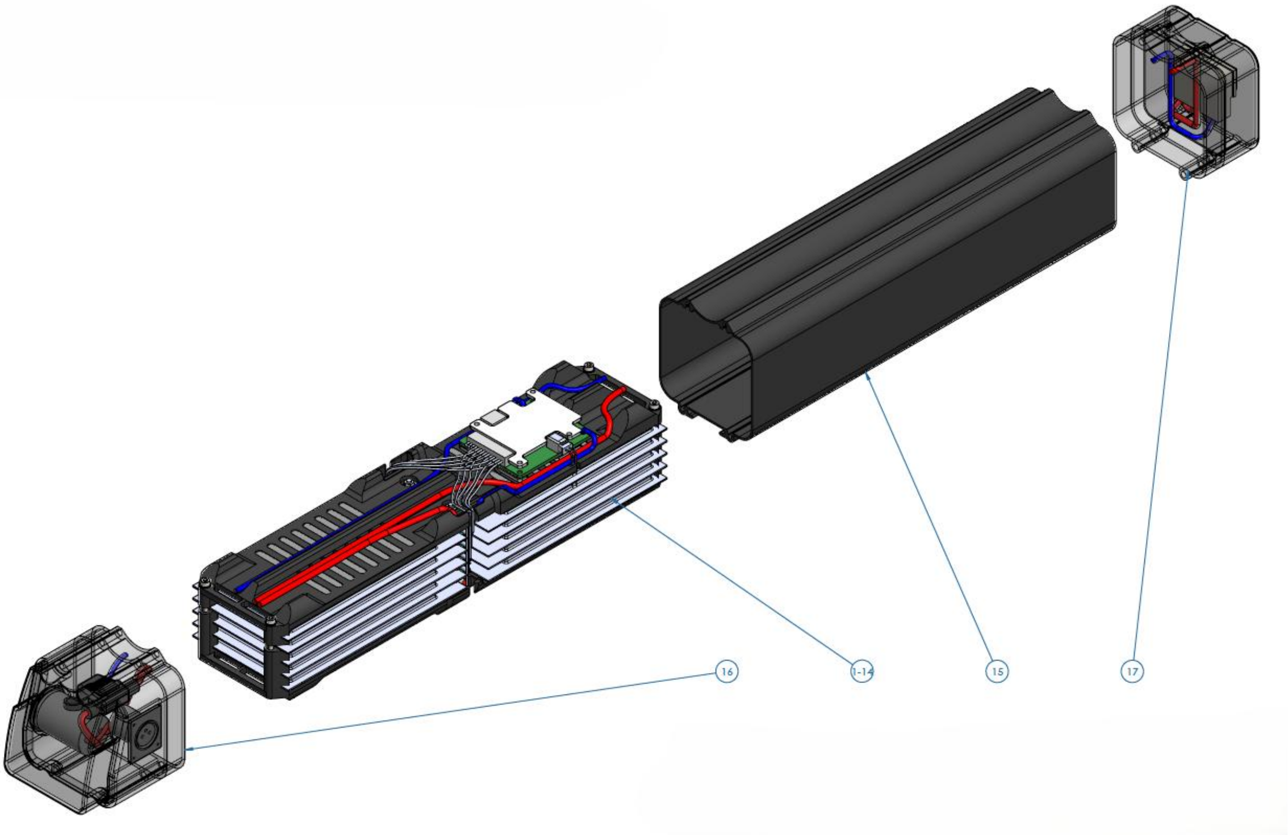

Figure 19. Exploded view of external components of the battery pack

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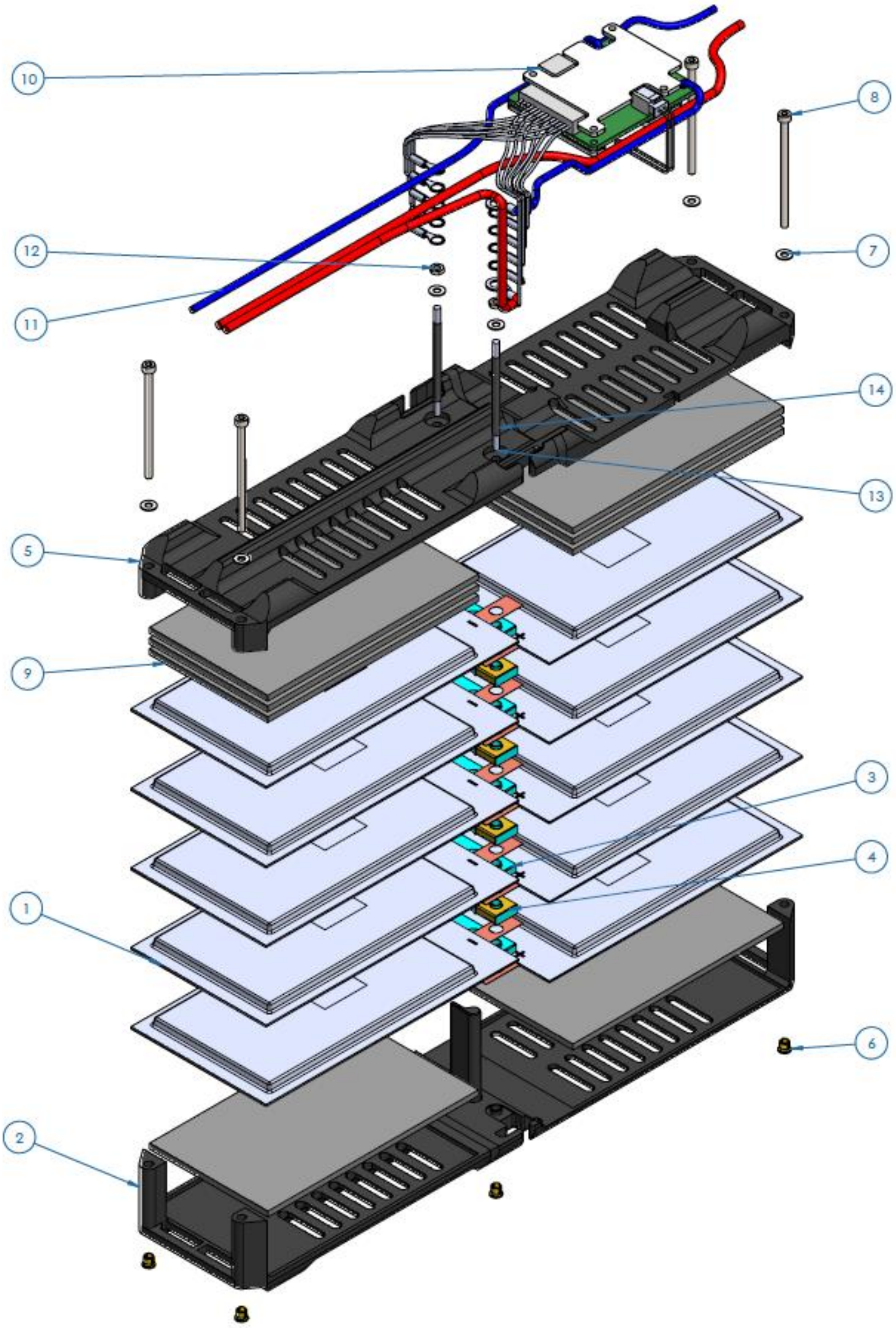

Figure 20. Exploded view of the battery cell frame.

Table 5.BOM of the final components of the F4L battery pack.

N	QTY	PART NUMBER	DESCRIPTION	MATERIAL
1	10		NESSTEC Pouch Cell	-
2	1	F4LT48_001	Lower Cell Frame	ASA
3	5	F4LT48_003-A	Contactor ASM A	ASA and Copper
4	4	F4LT48_003-B	Contactor ASM B	ASA and Copper
5	1	F4LT48_002	Upper Cell Frame	ASA
6	6		RS Thread insert M3	Brass
7	6		Washer ISO 7089 - 3	Steel
8	4		Socket Head Screw M3x55 ISO 4762	Steel
9	8		Compression Pad 125x70x3mm	EVA Foam
10	1		JBD BMS 7-14S 20 A	-
11	1	F4LT48_006	Cells Frame Wiring ASM	Copper and polymer
12	2		Hexagon Nut M3 x 55 DIN 934	Steel
13	2		Threaded rod M3 x 55 DIN 975	Zinc plated steel
14	2		Heat-shrinking tubing DIAM 3 mm	Polyolefin
15	1	F4LT48_403	Battery Casing	Aluminium
16	1	F4LT48_405	Battery Casing Top Lid	Plastic
17	1	F4LT48_401	Battery Casing Bottom Lid	Plastic

6. Assembly and validation of the prototype

Before starting the final assembly, the contactors were tested alone with the lower casing to prove the stickability and to check the final height of the screws, without compromising the battery cells.

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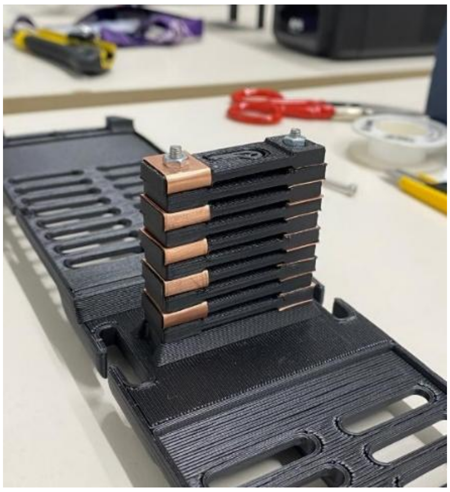

Figure 21. Contactor stacked with the contactor copper plate and secured in the lower frame.

The process of assembly begins with the adhesion of the compression pads on each of the sides of the lower and upper cell frame. In the lower cell frame, an M3 insert must be added in each of the designated holes. To do this, a soldering iron with a fine tip can be used to heat the metal insert, allowing it to fuse with the plastic as it is pressed into place.

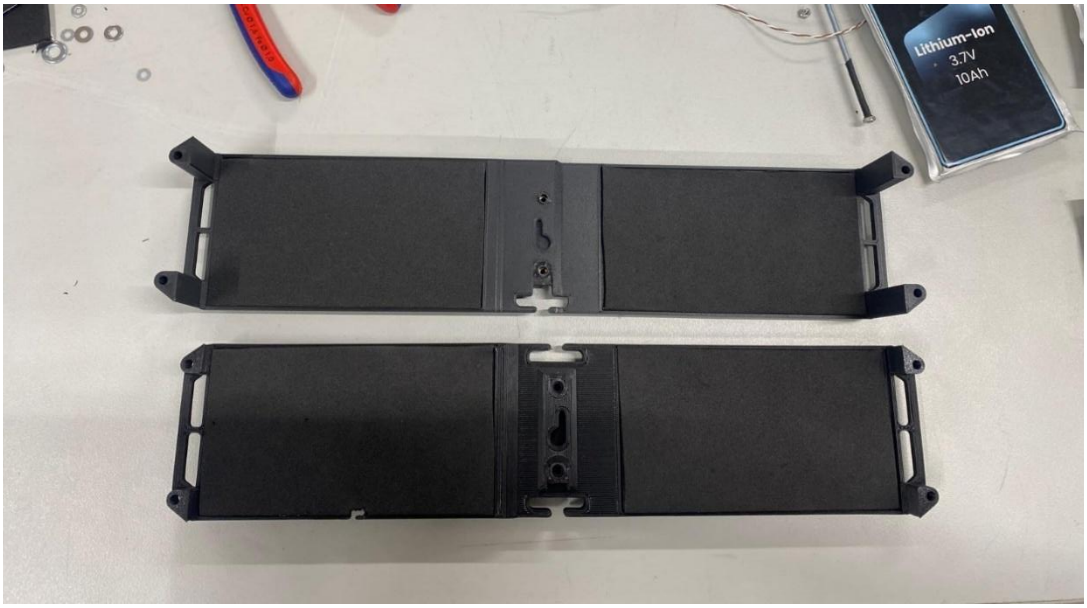

Figure 22. Upper and lower cell frame with the compression pads.

A protective layer is added to the threaded rods using heat-shrinking tubes, leaving both ends exposed to allow threading from both sides. To align the cells, the threaded rods are first screwed into the lower cell frame. The cells are then assembled in the correct order, placing a BMS sensor ring between

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each cell, always aligned to read the positive terminal (Figure 23 and Figure 24).

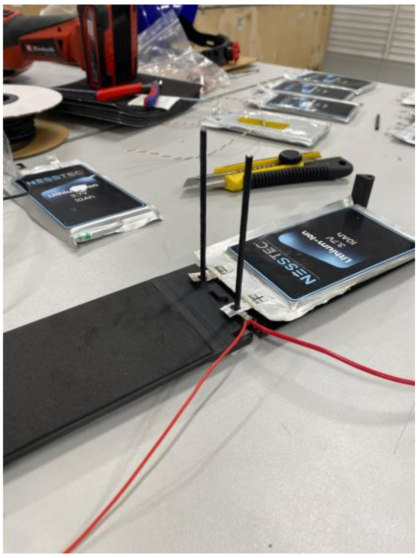

Figure 23. Threaded rod covered in heat-shrinking tube mounted on the lower cell

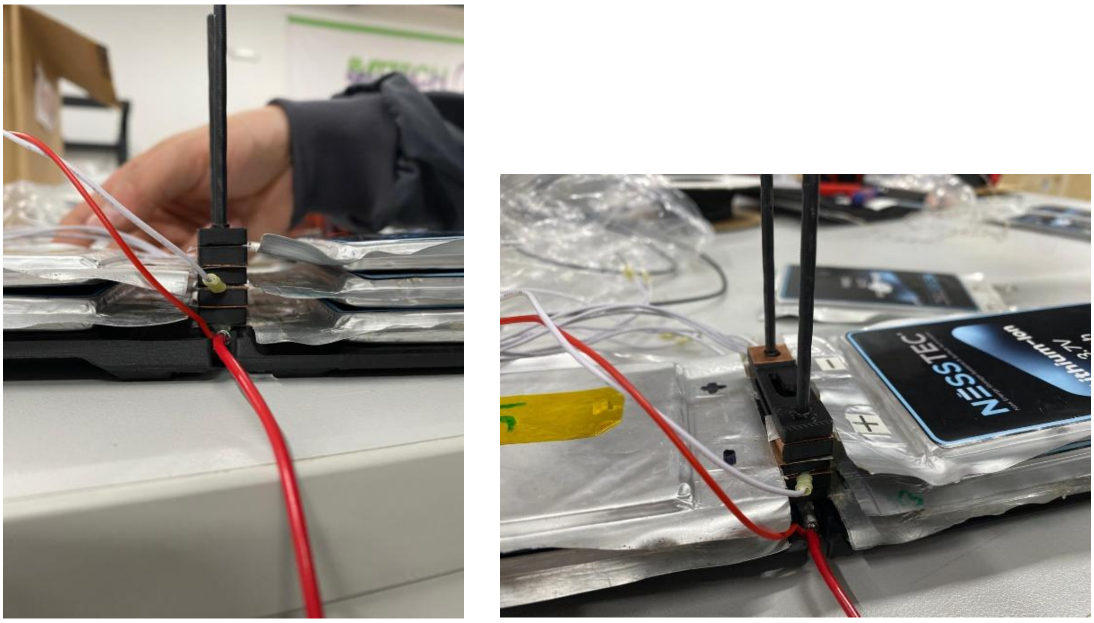

Figure 24. (Left) Side view of half of the cells already installed in the battery, along with their corresponding sensors. (Right) Five cells already mounted in the battery pack.

Once all the cells and their corresponding sensors are in place, the assembly is closed with the upper cell frame.

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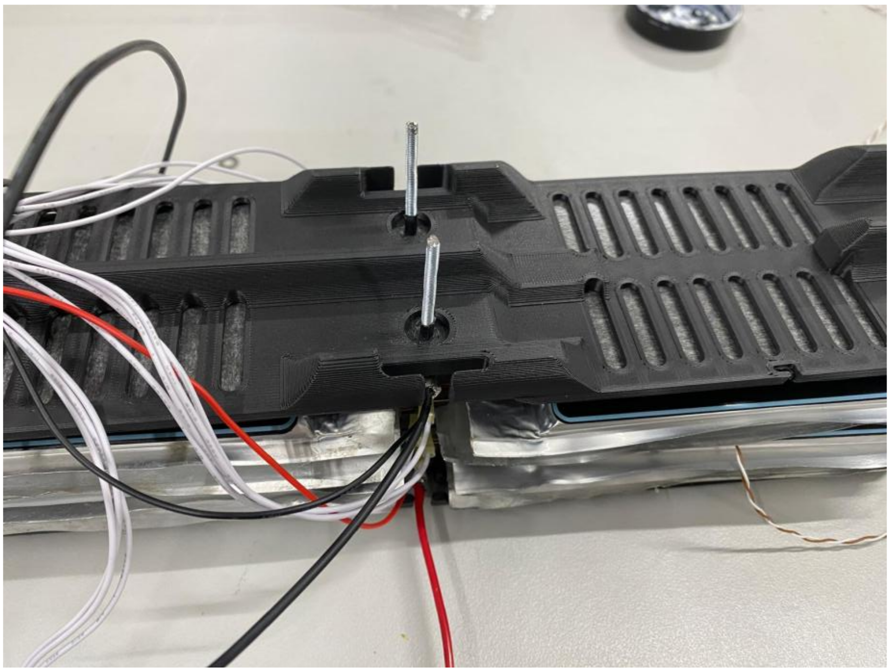

Figure 25. Upper view of the casing.

During the assembly process, the temperature of the cells must be monitored to detect any potential local overheating.

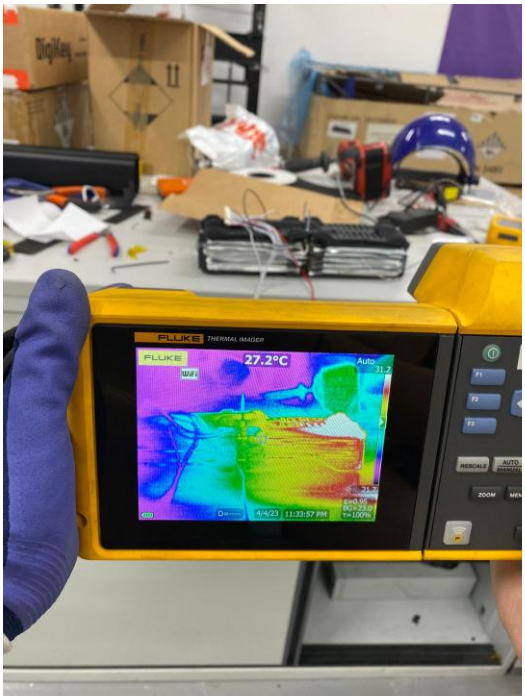

Figure 26. Thermal imager checking on the battery pack.

Finally, the assembly is secured and pressure is applied to the cells and contactors using a washer and a nut. The excess length of the threaded rods is then trimmed from the top to ensure the pack fits properly into the battery casing.

Figure 27. Fastening of the upper cell frame along with the washer and nut.

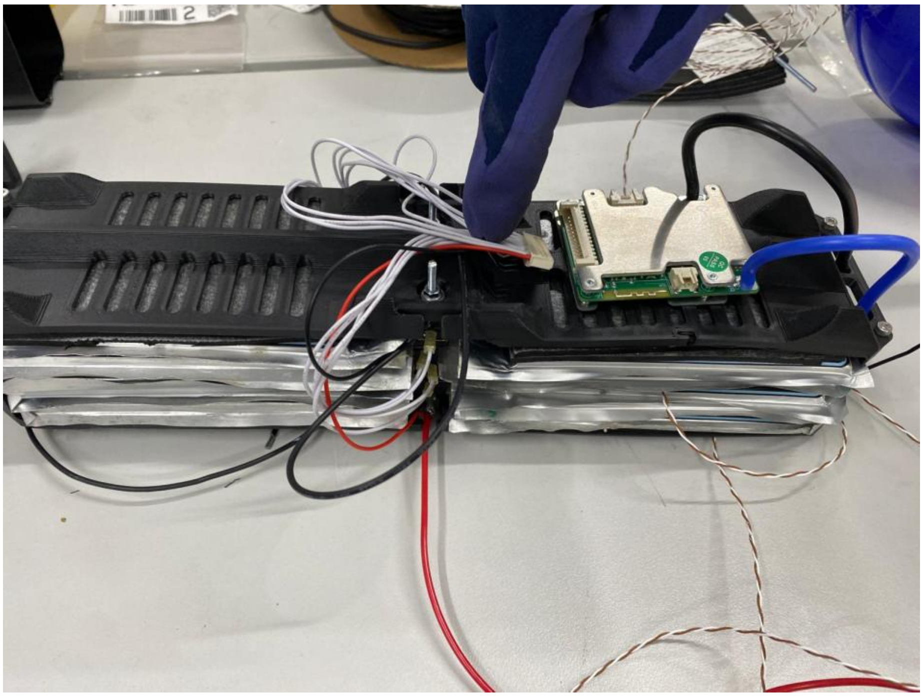

Figure 28. BMS positioning on the upper cell frame of the battery.

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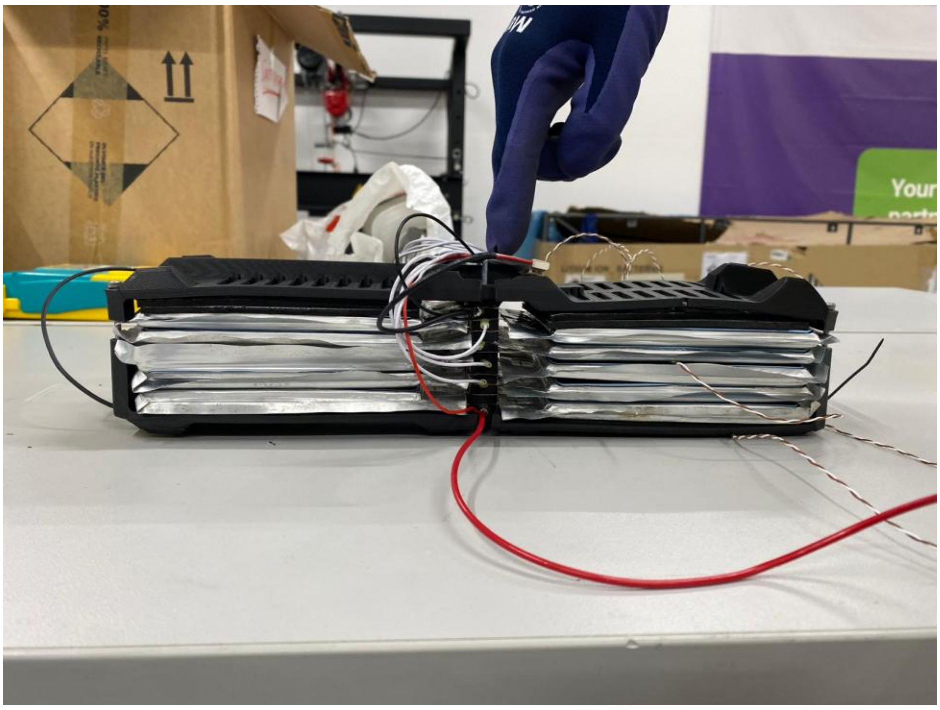

Figure 29. Side view of the whole battery pack.

Figure 30. Reused battery casing with F4L logo.

Once the prototype has been assembled, validation tests followed. To this end, the prototype was tested outside of the metallic chassis, as shown in Figure 30. First the BMS was implemented, connecting it as shown in Figure 19, by connecting the absolute positive and negative wires, and each individual voltage sensing wiring in the pin inlet, as well as the thermistor temperature sensor. This allows for a quick but effective monitoring of the pack status, as well as individual cell monitoring. Once the BMS software was verified to be operational and reporting correct cell values, the validation proceeded.

Early observations via BMS monitoring indicated that several cells had lost most of their voltage—some nearing 0V—despite having been individually charged prior to the assembly as previously mentioned. This enabled safe monitoring and control of internal parameters during a slow charging process.

During this controlled charge at C/10 or 0.6A, most functioning cells increased their voltage as expected. However, a subset of cells only partially recovered (reaching voltages above 2V from nearly 0V), and others remained at critically low levels. Notably, after charging ceased and the external circuit was opened, the partially recovered cells exhibited rapid self-discharge behavior to the previous voltages. Ultimately, only six cells were deemed to be functioning reliably.

These findings highlight the challenges and potential safety concerns associated with testing a battery pack composed of degraded cells. The issues observed likely stem from internal short circuits or severe capacity loss, indicating that the cells were in an unsuitable condition for performance validation. Despite this, the design validation objectives of the task were achieved, particularly regarding the efficient and flexible assembly approach. The prototype allowed for rapid and manual assembly/disassembly without welding, in line with the design criteria.

7. Eco-design principles used

The eco-design matrix developed by IREC was completed. In this matrix, the eco-design actions applied to the battery were marked, covering the stages of cell/pack manufacturing, use phase, and end-of-life.

In the battery prototype multiple eco-design strategies were implemented. The design prioritizes modularity and ease of disassembly, using mechanical, weldless joints and avoiding adhesives, which facilitates repairability, reuse of components and efficient material separation at end-of-life.

In terms of material selection, the battery avoids toxic substances and composite materials, opting instead for recycled and recyclable metals, especially in the casing and cell components (e.g., aluminium, cobalt, lithium). From a manufacturing standpoint, recycled aluminium profiles were used to lower energy consumption and waste.

The assembly process was designed to be straightforward, with easily accessible joints located on the same side of the battery, and a minimal number

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of fasteners that do not require special tools. This ensures that maintenance and eventual dismantling are as efficient as possible. Altogether, this design demonstrates commitment to eco-design by prioritizing circularity, repairability, and the responsible use of resources throughout the battery's life cycle.

The detailed eco-design matrix is provided in the **annex**.

8. Documentation for manufacturing, assembly and disposal phases

The documentation required for the manufacturing and assembly of the battery is included in the **annex**. It contains the 3D model, technical drawings with exploded views, a detailed breakdown of standard parts and joints, as well as the electrical connections between the BMS and each individual cell.

9. Conclusion

The resulting design for the F4L battery pack aligns with eco-design principles and strategies, such as the use of recycled or reused materials, no welding of any components on the electronic side, and a modular system that allows easy assembly, disassembly and direct access to the inside of the casing, for potential replacements or reparations. This approach prioritizes circularity and extends the product's lifecycle through maintainability and reusability.

Although, the actual functionality of the battery overall could not be tested properly, this was primarily due to the inherent challenges associated with using recycled battery cells. Several of the cells presented signs of degradation or damage, such as swelling or leakage, which are common risks when working with second-life components. These limitations affected the ability to carry out complete charge and discharge testing of the pack. However, such functional tests are expected to be feasible in the future, once cells in suitable condition become available.

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11. Annexes

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