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# Consolidated requirements

## *High-Voltage Spinel LNMO Silicon-Graphite Cells and Modules for Automotive and Aeronautic Transport Applications*

*Horizon Europe | HORIZON-CL5-2021-D2-01-02*

*Advanced high-performance Generation 3b (high capacity / high-voltage)*
*Li-ion batteries supporting electro mobility and other applications*

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# PROJECT ABSTRACT

HighSpin aims to develop high-performing, safe and sustainable generation 3b high-voltage spinel LNMO||Si/C material, cells and modules with a short industrialisation pathway and demonstrate their application for automotive and aeronautic transport applications. The project addresses in full the scope of the HORIZON-CL5-2021-D2-01-02 topic, setting its activities in the “highvoltage” line. The project objectives are:

- Further develop the LNMO||Si/C cell chemistry compared to the reference 3beLiEVe baseline, extracting its maximum performance.
- Develop and manufacture LNMO||Si/C cells fit for automotive and aeronautic applications.
- Design and demonstrate battery modules for automotive and aeronautic applications.
- Thoroughly assess the LMNO||Si/C HighSpin technology vs. performance, recyclability, cost and TRL.

The HighSpin cell targets 390 Wh/kg and 925 Wh/l energy density, 790 W/kg and 1,850 W/l power density (at 2C), 2,000 deep cycles, and 90 €/kWh cost (pack-level). The project activities encompass stabilisation of the active materials via microstructure optimisation, the development of high-voltage electrolyte formulations containing LiPF6 and LIFSI, high-speed laserstructuring of the electrodes, and the inclusion of operando sensors in the form of a chip-based Cell Management Unit (CMU).

HighSpin will demonstrate TRL 6 at the battery module level, with a module-to-cell gravimetric energy density ratio of 85-to-90% (depending on the application). Recyclability is investigated, targeting 90% recycling efficiency at 99.9% purity. HighSpin aims at approaching the market as a second-step generation 3b LNMO||Si/C in the year 2028 (automotive) and 2030 (aeronautics), delivering above 40 GWh/year and 4 billion/year sales volume in the reference year 2030.

# LIST OF ABBREVIATIONS

| Acronym / Short Name | Meaning |
|---|---|
| AC | Alternating Current |
| APU | Auxiliary Power Unit |
| BEA | Battery Electric Aircraft, pure electric vehicle without other power source. |
| BEV | Battery Electric Vehicle |
| BMS | Battery Management System |
| BOL | Beginning of Life |
| BP | Battery Pack |
| C-rate | The measurement of current with which a battery is charged and discharged relative to the battery's capacity |
| CD | Charge Depletion |
| DC | Direct Current |
| DOD | Depth of Discharge |
| EIS | Electrochemical Impedance Spectroscopy |
| EOL | End of Life |
| EOW | Empty Operation Weight |
| EPA | Environmental Protection Agency |
| GHG | Greenhouse Gas Emissions |
| HEA | Hybrid Electric Aircraft, combination of two power sources, such as electric and petrol |
| ICE | Internal Combustion Engine |
| kWh | Kilowatt-hour |
| LNMO | Lithium Nickel Manganese Oxide |
| MTOP | Maximum Take-off Power |
| MTOW | Maximum Take-Off Weight |
| NEDC | New European Driving Cycle |
| OEM | Original Equipment Manufacturer |
| PHEV | Plug-in Hybrid Electric Vehicle |
| RMS | Root Mean Square |
| RTCA | Radio Technical Committee for Aeronautics |
| RTCA DO | RTCA Document number |
| Si/C | Silicon Carbide |
| SOC | State of Charge |
| SOE | State of Energy |
| SOH | State of Health |
| TR | Thermal Runaway |
| TRL | Technology Readiness Level |
| WLTC | Worldwide Harmonized Light Vehicles Test Cycle |
| WLTP | Worldwide Harmonized Light Vehicles Test Procedure |
| WP | Work Package |

# EXECUTIVE SUMMARY

In HighSpin’s project tasks T1.1 and T1.2, vehicles and use cases for automotive and aeronautic applications, as well as corresponding sets of performance and safety requirements for these applications were defined. These were documented in deliverables *D1.1 Requirements for automotive application* and *D1.2 Requirements for aeronautic application*. These requirements are specified for the cell-level as well as module level.

In this document, requirements from D1.1 and D1.2 (i.e. for both automotive and aeronautic applications) are combined to identify the overlap as well as any potential synergies. The present document provides a merged set of requirements that are essential for both automotive and aeronautic transport application. These consolidated requirements cover performance, safety, and sustainability, and will be used as input to for materials development in Work Package (WP) 2, cell and module development in WP5, and for the validation/verification of demonstrators (cells and modules) in WP6.

For the automotive transport applications, two types of reference vehicles are chosen (cf. D1.1): an A-segment BEV and an urban truck. The aeronautic transport vehicle requirements are on the other hand derived from two different categories, namely Battery Electric Aircraft (BEA) and Hybrid Electric Aircraft (HEA) (cf. D1.2). Moreover, non-propulsion batteries are also briefly characterised in this document.

Safety requirements are crucial to operate the cells and the modules in normal and extreme conditions. Since batteries are considered dangerous goods, safe transportation of the batteries by road and air should be considered. The UN38.3 battery safety performance test procedure provides set of tests which can be the basis for permits to transport the cells. These requirements are provided in this document. In addition, the safety requirements for the aeronautic module are given based on the RTCA DO guidelines.

Sustainability is an aspect that is commonly overlooked in the requirements. A further elaboration of sustainability topics as they relate to the demonstrator design activities was undertaken in a three-part eco-design workshop; these will be documented more extensively separately. Here, some aspects such as use of materials, cycle life improvement and end of life assessment are already considered.

Overall, the consolidated requirements provide the baseline for the development and manufacturing of the automotive and aeronautic cells as well as the aeronautic module, all of which are in scope of the project activities. For the automotive module, HighSpin intends to use an existing design from its predecessor project 3beLiEVe, therefore design activities in this area are not foreseen.

# 1 INTRODUCTION

The cell level and module requirements for the automotive and aeronautic transport applications are established in the previous HighSpin deliverables, D1.1 and D1.2. In this document, the consolidation of those established requirements is provided to identify the overlapping requirements.

The requirements formulated in D1.1 (for automotive) and D1.2 (for aeronautic) reflect the bottom-up requirements coming from vehicle level. The requirements coming from the topic (HORIZON-CL5-2021-D2-01-02), to which this project responds, give global top-down values/KPIs. In this present D1.3, the bottom-up values for automotive and aeronautic, as well as the top-down values are merged and compared. For evaluation of cell performance, the more stringent of the two are applied. We consider that the more detailed elaboration of bottom-up vehicle values can provide valuable detail on the application of the global top-down values in the testing and evaluation phase. The merged/overlapping requirements are compared to the global, top-down KPIs from the topic, which are:

- Gravimetric, volume energy density at cell level of 350-400 Wh/kg, 750-1000 Wh/l respectively.
- Power density at cell level of 700 W/kg, 1500+ W/L.
- For high voltage application, operation at 4.7+ Volt.
- 3000+ and 2000+ deep cycles for high capacity and high voltage applications respectively.
- Cost at pack level < 100 euro/kWh.

The above global, top-down KPIs are in any case preserved. Figure 1 shows the merger process. The consolidated requirements from D1.3 are used as the reference against which to develop the testing objectives and protocols in D1.4.

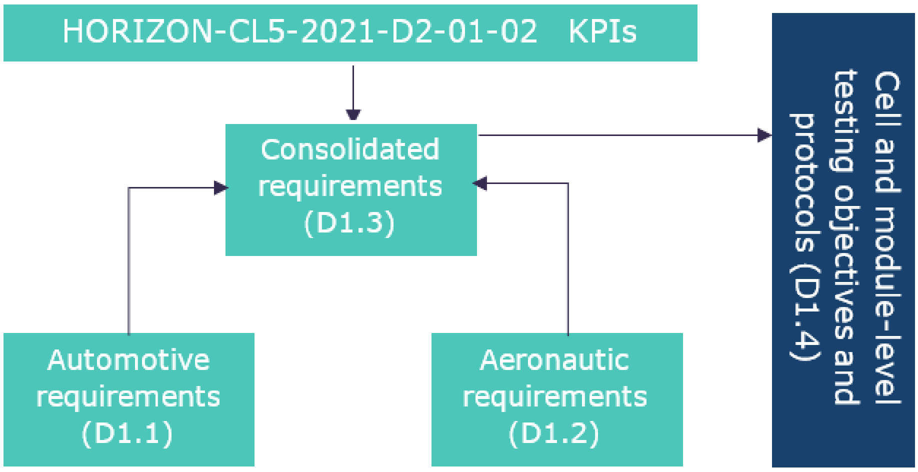

*Figure 1: Relation of requirements*

In addition to the performance and safety requirements, some sustainability aspects will be also included in this report.

## 1.1 OBJECTIVE

The objective of this report is to consolidate the automotive and aeronautical requirements provided in deliverables D1.1 and D1.2 respectively. This results in the present deliverable *D1.3 Consolidated requirements* with all safety, sustainability and performance requirements and will function as input for WP2 and WP5 and finally for the validation/verification in WP6.

## 1.2 REPORT STRUCTURE

Section 2 recalls the reference vehicles for the automotive and aeronautic application that were defined in the preceding deliverables and provides use-cases and load profiles for the selected reference vehicles. Section 3 gives the safety requirements on cell and module level, followed by the performance requirements, starting with a recap of the automotive and aeronautical requirements in sections 4.1 and 4.2 respectively. In section 4.3 the requirements have been merged for the HighSpin project.

Finally, some sustainability requirements can be found in section 5, including aspects such as cycle life improvement, material choice and end of life processing.

# 2 LIST ELECTRIC REFERENCE VEHICLES

The automotive requirements as defined in HighSpin's predecessor project, 3beLiEVe, were the starting point for the definition of automotive requirements for HighSpin, which were refined and documented in *D1.1 Requirements for automotive application*.

There is no similar starting point for the aeronautic requirements since aviation was out of the scope of the 3beLiEVe project. Therefore, a battery electric aircraft (BEA) and hybrid electric aircraft (HEA) have been defined in *D1.2 Requirements for aeronautic application*.

This chapter briefly summarises the selected vehicles and user applications found in *D1.1 Requirements for automotive application* and *D1.2 Requirements for aeronautic application*. The use-cases are described and the expected load profiles for the selected vehicles and user applications are provided.

## 2.1 VEHICLE SELECTION

The automotive vehicle selection for HighSpin resulted in the Fiat 500 electric, and the VOLVO FL Electric (Figure 2). These two endpoints span the range from light passenger vehicles on one hand to multi-purpose urban trucks platforms as a vocational vehicle on the other hand.

*Figure 2 – Reference vehicles for requirements: passenger vehicles – city car BEV (Segment A/B, Fiat 500; vocational vehicles – VOLVO FL Electric (image source: electrive.net*)

For aeronautical applications, two vehicles are selected that utilise the battery for propulsion, and a third aircraft is referenced for non-propulsive applications. The reference aircraft with propulsion batteries are the Pipistrel Velis Electro and UNIFIER19. A Boeing 787 is used as a reference for non-propulsive battery application.

*Figure 3 – Reference vehicles for aeronautical application: Pipistrel Velis Electro (left); and UNIFIER19 (right)*

## 2.2 AUTOMOTIVE USE CASE

The main use case for automotive to assess the usability of the cells developed under the HighSpin project is based on a passenger car driving between 12 000 and 15 000 km a year. With an expected total lifetime of 15 years this results in a total distance driven between 180 000 and 225 000 km.

To simulate this type of usage on the battery a load profile will be determined based on the standardised WLTC class 3 (for cars with a power to unladen mass ratio of > 34W/kg). In Figure 4 is shown the relation of speed and time during a cycle based on the WLTP [1].

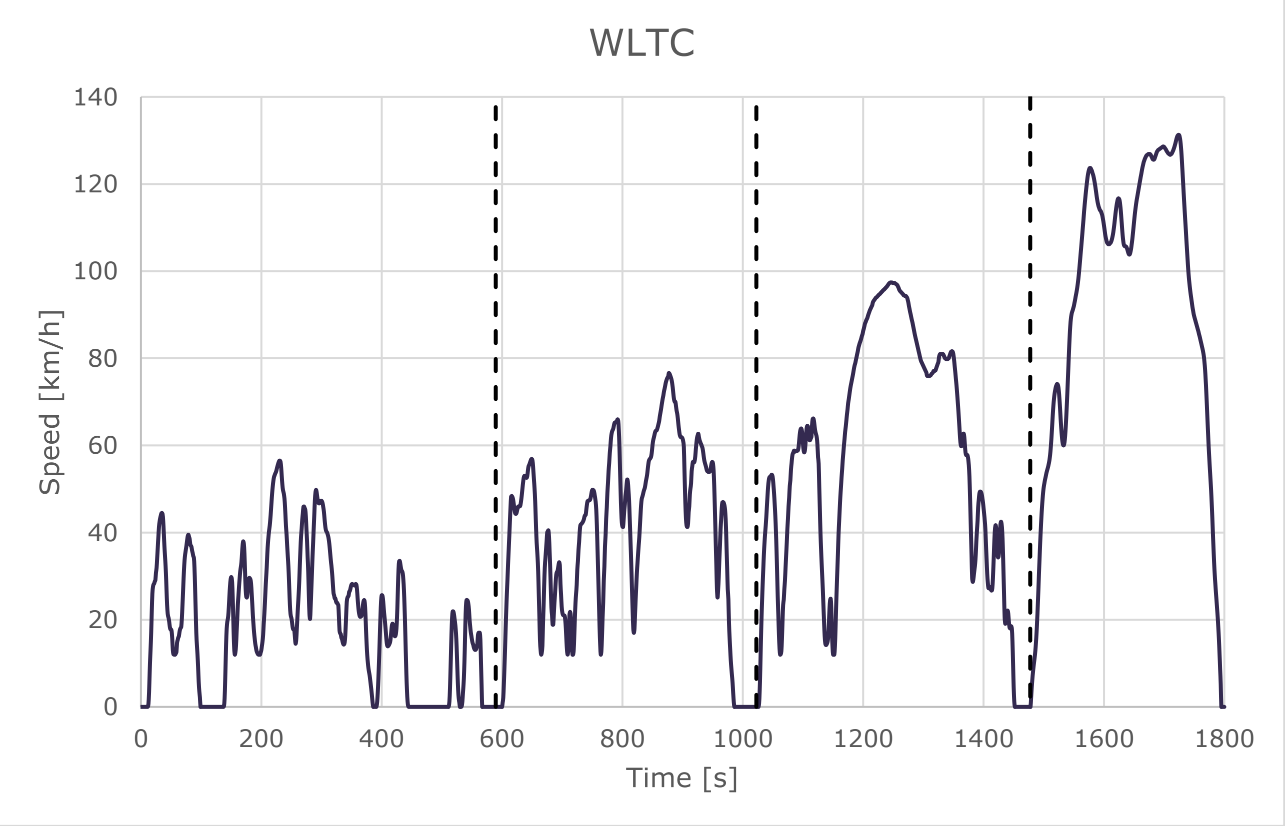

*Figure 4 – WLTC cycles for class 3 vehicles*

One cycle takes 30 minutes (1800 seconds) during which the car travels a total distance of approximately 23.2 km and is split in four segments (indicated by dashed lines):

- Low phase
- Medium phase
- High phase
- Extra high phase

These four segments represent different scenarios such as slow urban traffic with many starts and stops, and cruising on the highway at high speed. Based on expected vehicle mass and total battery capacity the power profile per quantity battery cells can be derived from this graph.

## 2.3 AERONAUTIC USE CASE

Two use-cases and load profiles are provided in this section. The first use-case and mission profile is based on the Pipistrel Velis Electro for BEA applications. The second mission profile is for a HEA application, based on the UNIFIER19. Finally, a general description is provided regarding the load profile for non-propulsive application.

### 2.3.1 BEA application

A battery electric aircraft (BEA) uses batteries as its only source of energy. Currently the only type of certified battery electric aircraft is the Pipistrel Velis Electro. Since no other energy source available, the batteries need to provide sufficient energy for the entire duration of the flight.

The Velis electro is mainly used to provide flight training and short leisure flights. Other use-cases of BEA using the cells developed by the HighSpin project would mainly be focussed on flights of a maximum duration of 2 hours. In addition to flight training and leisure flights, this could include short-haul commuter flights.

Table 1 provides the required power levels for each flight segment. The power levels are provided in W/kg on cell level for easier comparison. After the landing segment there is still 30% SOC remaining for a potential go-around which requires a similar power level as take-off and can only be performed when SOC is at least 15%.

*Table 1 – Load profile for BEA applications*

| Flight phase | Power (W/kg) | Time (s) |
|---|---|---|
| Taxiing | 45 | 300 |
| Take-off | 500 | 90 |
| Climb | 420 | 150 to 600 |
| Cruise | 170 to 320 | / |
| Descent | -100 to 0 | 200-800 |
| Landing | -100 to 0 | 120 |

Please note that duration of climb and descent is dependent on rate of climb/descent and desired flight level. There is no duration provided for cruise as this is dependent on flight mission. The power level for cruise is dependent on desired cruise speed (170W/kg is slower but more economical, 320 W/kg is faster at the cost of range). During descent and landing the propeller/motor could be used to recoup some of the energy to slow down the aircraft.

Cells that complete this load profile successfully can be used for a wide variety of CS-23 aircraft such as a small two-seater like the Pipistrel Velis Electro or larger 19-seat commuter aircraft.

### 2.3.2 Mission profile HEA

Hybrid electric aircraft (HEA) use two different types of energy sources for propulsion. In general, the battery is considered the secondary power source, which can be used to reduce peak loads and stabilise power supply while electrical power is supplied by the main power supply such as a kerosine-powered turbine, or hydrogen fuel stacks. In contrast to BEA, HEA can recharge the batteries during flight.

The use-case of HEA is much broader compared to BEA as the maximum range/endurance is not limited by the batteries. HEA could therefore be used for long haul flights. Especially airports with strict noise levels could be interesting as HEA could take off and perform the initial stage of the climb fully electric, reducing noise levels significantly.

The load profile in Table 2 provides the load profile for the batteries only. The battery is used for taxiing, and take-off, and can be recharged during cruise. Dependent on the second energy source, the battery could be used as balance plant to stabilise power supply to the motors.

*Table 2 – Load profile for HEA applications*

| Flight phase | Power (W/kg) | Time (s) |
|---|---|---|
| Taxiing | 15 | 300 |
| Take-off | 1800 | 120 |
| Climb | 1400 | 300 |
| Cruise | -180 | / |

For HEA applications the C-rate is expected to be much higher compared to BEA because utilisation of the battery is reduced to only take-off and climb while maximum required power is higher.

### 2.3.3 Non-propulsive battery application

Unlike most airliners, the Boeing 787 uses a no-bleed system which does not require a pneumatic system to start the engines or power the flight control surfaces. Instead, APU batteries are used to start the APU which then can be used to power the engines. All flight control surfaces are powered electrically as well.

In this case, the batteries are mainly used to start up the aircraft, start the APU and provide emergency power in case power supply from the engines and APU in mid-flight fail.

During normal operations the batteries are continuously charged by generators in the engines to make sure the batteries are always fully charged.

There are no load profiles available to any of the partners of HighSpin for this application.

# 3 SAFETY REQUIREMENTS

Safety has the highest importance regarding the development of new cells and the design of the battery modules/pack. The aviation industry has an outstanding track-record regarding safety and airline accidents are extremely rare thanks to comprehensive investigations that are performed after each accident or incident. Safety is paramount also for cars and has improved quite significantly already. Some OEMs even collect real-world data, such as Volvo Cars who have been sending research teams to over 43000 crashes in Sweden since 1970 [2].

The safety requirements in this project have been split between cell level and module level, found in in section 3.1 and 3.2 respectively. All requirements listed under cell level requirements must be met at cell level while the requirements at module level can be met on module level or on cell level.

## 3.1 CELL SAFETY REQUIREMENTS

The main purpose of the cell level safety requirements is to ensure that individual cells can easily be transported during the manufacturing process and are based on the UN38.3 battery safety performance test procedure [3].

### 3.1.1 Altitude simulation

To simulate operations at high altitude, the cells and batteries should be stored at the pressure $p = 11$ kPa and $T = 25 \pm 5$ °C for at least six hours. During this time no leakage, venting, disassembly, rupture or fire should appear.

### 3.1.2 Thermal test

To simulate operations at high and low temperature, the cell and batteries are store at high temperature equal to 72 ± 2 °C following the lower temperature at -40 ± 2 °C for minimum duration of six hours. During this time no leakage, venting, disassembly, rupture or fire should appear.

### 3.1.3 Vibration

Vibrations during transport are simulated by the sinusoidal wave with sinusoidal wave of different frequency rated (7Hz-200Hz). During this time no leakage, disassembly, rupture or fire should appear.  This applies to the cells and the batteries with mass lower than 12 kg.

### 3.1.4 Shock

To assess the cumulative shock impacts during transport, the small cells and batteries are subjected to the half-sine pulse test with peak acceleration up to 150g and 6 ms pulse duration. During this time, no leakage, no venting, no disassembly, no rupture, and no fire should appear.

### 3.1.5 External short circuit

This test is used to make sure the cell is safe and does not cause any hazardous situations if an external short circuit occurs during transportation.

First the cell needs to be heated homogeneous to $T = 56 \pm 3\,°C$. Next, the cell is short circuited with a resistance of less than $r = 0.1\,\Omega$. The cell is not allowed to heat up more than $T = 170\ °C$, or cause fire, rupture or disassemble.

### 3.1.6 Crush

To simulate mechanical abuse, the cells and batteries are subjected to the crushed with a gradual speed of 1,5 cm/s until the following scenario is reached:

1. The applied force reaches 13 kN ± 0.78 kN;
2. The voltage of the cell drops by at least 100 mV; or
3. The cell is deformed by 50 % or more of its original thickness.

During this time, the temperature should not exceed 170 °C. In addition, there should be no disassembly, no rupture and no fire.

### 3.1.7 Overcharge

To test if the cells can endure overcharge during shipping the cells need to be overcharged for 24 hours and should not disassemble or cause fire up to 7 days after the initial test. Charging is done by a rate of twice the recommended maximum charge current to a voltage of at least twice the maximum voltage.

### 3.1.8 Forced discharge

To simulate incorrect installation of the cell, a forced discharge test is needed to prove the cells can be safely discharged at their maximum discharge current and do not disassemble or cause fire up to 7 days after the test was performed.

## 3.2 MODULE SAFETY REQUIREMENTS

The targeted hazard level for the batteries is compliance to UN38.3, DO-311, AC20-184 and ARP4754. UN38.3 should be met at cell level as discussed in the previous section and DO-311A shall be met at module level. ARP4754 and AC20-184 are guidelines for best practice and describes the entire development cycle for aircraft and systems to help minimise the chance a requirement is missed. Because these guidelines are concerning the method how the design process should be performed rather than product specific requirements, there are no specific requirements for the HighSpin battery cell or battery module/pack.

The list of safety requirements on module level can be found in DO-311A. These include requirements regarding fire protection, electrical protection, venting provisions, and environmental safety [4]. The rationales of these requirements are given below.

### 3.2.1 Venting Provisions

The flammable, toxic or corrosive gases, smoke, soot particulates or fluids must be contained inside the battery system during normal operations. In case of a thermal runaway this dangerous substance should be emitted safely outside using a venting provision in accordance with venting provision category B. In addition, the system must be designed such that no foreign objects should block the venting provision.

### 3.2.2 Electrical Bonding

The battery system that are designed with electrically conductive cases, must incorporate provision to electrically conductive surface on hold down bars, brackets, or attachment points, which contains electrical bonding with airframe as applicable.

### 3.2.3 Dissimilar Bonding

Battery systems that contain different materials in the close locations must be protected against galvanic corrosion. In addition, the possible thermal expansion should be also considered in the design.

### 3.2.4 Insulation Resistance

The high voltage electrical power contacts of the battery system must be designed in accordance with the following requirements to prevent excessive leakage of current.

a. The insulation resistance value at duration of 60 seconds shall be not less than 10 megaohms.
b. The insulation resistance value after the environmental testing, as defined in section 2.3, shall not be less than 2 megaohms.

### 3.2.5 Handling Strength

The handles that are used to lift the battery system must be designed such that the handles can withstand static loads, which are twice the weight of the battery system. The battery container, cover, handle or handle mounts must also not break, bend, tear or crack during handling.

### 3.2.6 Cycling of High Rate Batteries

When the battery is charged or discharged at 120% of the maximum designed charging or discharging rate for at least 100 cycles, the following aspects must be adhered to.

a. Any fragments should not be released outside of the battery system.
b. No flames, gas, smoke, soot, or fluid should escape the battery system.
c. No rupture or deformation of the battery system beyond the specified dimensional tolerance.

### 3.2.7 Rapid Discharge at Short-Time Operating High Temperature

When the battery is discharged rapidly at the so called Short-Time Operating High Temperature, as stated in Section 4 of RTCA/DO-160, the following aspects must be adhered to.

a. Any fragments should not be released outside of the battery system.
b. No flames, gas, smoke, soot, or fluid should escape the battery system.
c. No rupture of the battery system.
d. Battery thermal cut-off protection(s) should not be triggered during a full discharge EPV

### 3.2.8 Battery Thermal Runaway Containment

The following aspects should be complied when the battery undergoes into a thermal runaway condition:

a. Any fragments should not be released outside of the battery system.
b. No flames, gas, smoke, soot, or fluid should escape the battery system.
c. The escape of emission must be complied to the venting category B.

### 3.2.9 Explosion Containment

When an explosion occurs from one or more cells and ignition source is present, the battery must comply with following elements:

a. Any fragments should not be released outside of the battery system.
b. No flames, gas, smoke, soot, or fluid should escape the battery system except though designed venting provision.
c. The escape of emission must be complied to the venting category B.

### 3.2.10 Environmental safety requirements

For safe operation under extreme environmental conditions, the module should have provisions to keep the cells within their operational limits. In Table 3 are provided the requirements for temperature and altitude criteria. The module shall be able to operate under these conditions and allow full performance capability.

*Table 3 – Temperature and altitude criteria [5]*

| Requirement | Value | Unit |
|---|---|---|
| Operating low temperature | -20 | °C |
| Operating high temperature | +55 | °C |
| Altitude (pressure) | 7.6 (37.60) | km (kPa) |

# 4 PERFORMANCE REQUIREMENTS

Deliverables *D1.1 Requirements for automotive application* and *D1.2 Requirements for aeronautic application* from the HighSpin project already described the performance requirements for cells and modules. These requirements are summarised below in Table 4 for automotive requirements. The cell level and module level requirements for the aeronautic application are provided in Table 5 and Table 6, respectively. In Table 7 these requirements are combined into a single set of requirements.

## 4.1 AUTOMOTIVE PERFORMANCE REQUIREMENTS

In *D1.1 Requirements for automotive application* the requirements for a Fiat 500 electric passenger vehicle and a Volvo FL electric vocational vehicle have been analysed to form a set of requirements at cell and module level for the passenger and vocational vehicle. These requirements, which on cell and module level are formulated relative to the pack design proposed in D1.2, are reproduced in Table 4.

*Table 4 – Combined requirements from passenger and vocational vehicle*

| Requirement | Unit | Cell | Module | Comment |
|---|---|---|---|---|
| **Energy** | | | | |
| Nominal Energy at Beginning of Life (Battery System) | [kWh] | 0.132 | 1.06 | |
| Usable Energy at Beginning of Life (Battery System) | [kWh] | 0.119 | 0.95 | 90% of nominal energy at BoL |
| Usable Energy at End of Life (Battery System) | [kWh] | 0.095 | 0.76 | 80% of usable energy at BoL |
| Energy density | Wh/L | 750 | 450 | Based on information provided by OEMs with volumetric packaging efficiency of 60% |
| **Voltage [V]** | | | | |
| Nominal Voltage (Battery System) | [V] | 4.4 – 4.5 | 35 - 36 | |
| Voltage Range - Full Performance (Battery System) | [V] | 3.8 – 5.0 | 30-40 | Expect to achieve up to 4.9V with specified cell |
| Voltage Range - Reduced Performance (Battery System) | [V] | 3.3 – 5.0 | 26-40 | |
| Nominal and Voltage Range (Modular Pack) | [V] | - | <60 | |
| **Power [kW]** | | | | |
| Peak Discharge Power (2 s) - BoL | [kW] | 0.38 | 3 | |
| Peak Discharge Power (10 s) - BoL | [kW] | 0.31 | 2.5 | |

| | | | | |
|---|---|---|---|---|
| Continuous Discharge - BoL | [kW] | 0.22 | 1.75 | |
| Peak Charge Power (2 s) - BoL | [kW] | 0.47 | 3.75 | |
| Peak Charge Power (10 s) - BoL | [kW] | 0.38 | 3 | |
| Continuous Charge - BoL | [kW] | 0.313 | 2.5 | |
| Peak Discharge Power and Duration (2s) - EoL | [kW] | 0.30 | 2.4 | |
| Peak Discharge Power and Duration (10s) - EoL | [kW] | 0.25 | 2 | |
| Continuous Discharge - EoL | [kW] | 0.175 | 1.4 | |
| Peak Charge Power and Duration (2s) - EoL | [kW] | 0.375 | 3 | |
| Peak Charge Power and Duration (10s) - EoL | [kW] | 0.300 | 2.4 | |
| Continuous Charge - EoL | [kW] | 0.250 | 2 | |
| Continuous Charge - Plug-in Charging | [kW] | 0.069 | 0.55 | |
| Continuous Charge - Fast Charge - SoC range and time | [kW] | 0.313 | 2.5 | For 1500 s |
| **Current [A]** | | | | |
| Continuous Charge - Fast Charge - SoC range and time | [A] | 87.5 | 87.5 | maximum current that system will see for 10 s, limited by wiring and fusing.<br>**= 2.9 – 3.3 C for a 30Ah cell** |
| Max. Current in Charge (10 s pulse) | [A] | 100 | 100 | |
| **Usage patterns** | | | | |
| Duty cycles | | WLTP Class 3 | | |
| Usage Pattern | | OEM proprietary | | External temperatures, duty cycles, downtime periods; typical vehicle usage |
| Expected No. of Cycles / Range | Cycles | 1000 | | |
| **Life Expectation** | | | | |
| Range before EoL (SoC window) | % | 5 - 95 | | |
| Calendar Life | years | 15 | | |
| Energy Throughput before EoL | [kWh] | 141 | 1125 | For cell: equivalent to approx. 1065 full cycles relative to nominal energy at BoL; 1183 cycles relative to usable energy at BoL. |
| **Round trip efficiency** | | | | |
| Energy Efficiency [%] | % | 95 | | |

| | | | | |
|---|---|---|---|---|
| **Thermal – operating and storage conditions** | | | | |
| Typical Operating Temperature - Discharge (min, max) | °C | 0 to 45 °C | | |
| Extreme Operating Temperatures (min, max) | °C | -25 to 55 °C | | |
| Storage Temperature (min, max) | °C | -20 to 55 °C | | |
| Max Allowable Self Discharge (Wh/month) | Wh/ month | 0.31 | 2.5 | |

## 4.2 AERONAUTIC PERFORMANCE REQUIREMENTS

As already discussed in HighSpin *D1.2 Requirements for aeronautic application*, the aeronautic requirements are focused on fully electric fixed wing aircraft because the cell maximum specific peak power requirement for other aircraft like helicopters or eVTOL aircraft is out of the scope of this project.

### 4.2.1 Aeronautic cell requirements.

Below is given a table to summarise the aeronautic high-level battery requirements. A more detailed explanation for each requirement can be found in deliverable 1.2 Requirements for aeronautic application section 2.

*Table 5 – List of cell level requirements for aeronautic application*

| No. | Name | Value | Unit | Notes |
|---|---|---|---|---|
| 1 | Specific energy | 390 | Wh/kg | Global requirements coming from HORIZON-CL5-2021-D2-01-02 topic |
| 2 | Energy density | 925 | Wh/L | |
| 3a<br>3b | Specific power nominal<br>Specific power peak | 790 @2C<br>1200 @3C | W/kg | As stated in the KPI |
| 4a<br>4b | Power density nominal<br>Specific power peak | 1850 @2C<br>2775 @3C | W/L | As stated in the grant agreement. |
| 5a<br>5b | Fast charging time<br>Fast charging peak load | <15<br>5 | min<br>C | As stated in the grant agreement. |
| 6 | Minimum cell operational temperature | 10 | °C | Cells will be cooled or heated actively to optimise temperature window. |
| 7 | Maximum cell operational temperature | 50 | °C | Cells will be cooled or heated actively to optimise temperature window. |
| 8 | Cell survival temperature | -20 to +60 | °C | Nice to have |
| 9 | Self-discharge | <5% | - | At 100% SoC (open circuit) at 45 °C per month. |
| 10 | Battery cycle life | >2000 | - | Deep cycles. There is no single ageing profile available for aeronautic applications as this really depends on the application, instead deep cycles are used as a reference. |
| 11 | Cost at pack level | 90 | €/kWh | As stated in proposal |

|  |  |  |  |  |
|---|---|---|---|---|
| 12 | Max discharge | >3 | C | As stated in proposal |
| 13 | Cell capacity range | 10-25 | Ah |  |
| 14 | Cell sensor capabilities | SoC and SoH estimation, load balancing, TR detection and temperature sensor. |  |  |
| 15 | Hazard level | UN38.3, AC20-184, and ARP4754 |  | As stated in proposal |

### 4.2.2 Aeronautic module requirements

The final module level requirements are given in the table below. The rationale for each requirement can be found in deliverable 1.2 Requirements for aeronautic application section 3.

*Table 6 – List of module level requirements for aeronautic application*

| No. | Name | Value | Unit | Notes |
|---|---|---|---|---|
| 1 | Hazard level | UN38.3, DO311, AC20-184, and ARP4754 |  | As stated in proposal |
| 2 | Maximum battery pack voltage, consisting of several modules in series | 2000 | V | Expected maximum voltage for aviation application. There is no single module voltage level since this can vary a lot, depending on, among others, the mechanical design of the aircraft and physical constraints of the module. |
| 3 | Thermal monitoring | Cell level EIS/V/T sensor plus secondary safety features for aeronautics, (over/under voltage, temperature, current, short-circuit detection, vibration, shock |  | As stated in proposal |
| 4 | SoC/SoH monitoring |  |  | As stated in proposal |
| 5 | On-board EIS |  |  | As stated in proposal |
| 6 | Module-to-cell Gravimetric energy density ratio | >90 | % | As stated in proposal |
| 7 | Module is BMS agnostic | Yes |  | As stated in proposal |
| 8 | Specific energy | >350 | Wh/kg | As stated in proposal |
| 9 | Consistency of materials with eco-design principles (T1.3) | Yes |  | As stated in proposal |

## 4.3 HIGHSPIN CONSOLIDATED PERFORMANCE REQUIREMENTS

The consolidated performance requirements for the HighSpin project have been divided over cell- and module level requirements. The cell requirements will be the same for automotive and aeronautical applications, except for some small changes to the definition of DOD and EOL to meet some sector specific desirables. Finally, the module requirements have been split again between automotive and aeronautical requirements as there are stark differences, especially regarding sustainability and additional safety requirements specific to aviation.

### 4.3.1 HighSpin cell requirements

In Table 7 can be found the consolidated cell performance requirements for the HighSpin project, followed by the rationale for each requirement.

*Table 7 – HighSpin consolidated cell performance requirements*

| Req. ID | Name | Value | Unit | Notes |
|---|---|---|---|---|
| C01 | Specific energy | 390 | Wh/kg | Within range of call topic (350 – 400 Wh/kg) |
| C02 | Energy density | 925 | Wh/L | Within range of call topic (750 – 1000 Wh/L) |
| C03 | Voltage nominal | 4.4 | V | |
| C04 | Voltage maximum | 5 | V | In line with call topic of operation at 4.7+ V |
| C05 | Voltage minimum | 3.8 | V | Full cell performance |
| C06 | Voltage minimum | 3.3 | V | Reduced cell performance |
| C07 | Power peak discharge | 3.3 | C | 10 seconds |
| C08 | Power continuous discharge | 3 | C | |
| C09 | Power peak charge | 5 | C | 10 Seconds |
| C10 | Power continuous charge | 4 | C | |
| C11 | Minimum cell operational temperature | -25 | °C | Cells will be cooled or heated actively to optimise temperature window. |
| C12 | Maximum cell operational temperature | 55 | °C | |
| C13 | Cell survival temperature | -25 to +60 | °C | Nice to have |
| C14A | Cycle life automotive | 1000 | - | As provided by automotive OEM |
| C14B | Cycle life aeronautic | 2000 | - | Deep cycles (consistent with global top-down value of the call topic of 2000 cycles for high-voltage) |
| C15 | Calendar life | 15 | Years | |
| C16 | Energy efficiency | 95 | % | Round trip efficiency |
| C17 | Max allowable self-discharge | 0.23 | %/month | |
| C18 | On-board Thermal monitoring | Cell level EIS/V/T sensor plus secondary safety features for aeronautics (over/under voltage, temperature, current, short-circuit detection, vibration, shock) | | |
| C19 | On-board SoC/SoH monitoring | | | |

| | | |
|---|---|---|
| C20 | On-board EIS | |
| C21 | Hazard level | UN38.3 compliance |

#### *4.3.1.1 Specific energy*

The Maximum Take-off Weight (MTOW) is one of the Key Performance Indicator (KPI) in aircraft design. During the conceptual design and the preliminary sizing phase of the aircraft, the weight is defined to constrain the other design aspects such as wing and power-plant. In addition, any deviation of the weight after the preliminary design phase can cause tremendous impact on the performance and the cost of the aircraft. Although, in the automotive case, the weight may cause less or no implication during the initial design depending on the vehicle category. Therefore, the requirement for specific energy has been set at the maximum targeted by the HighSpin project, at 390 Wh/kg.

#### *4.3.1.2 Energy density*

Volume can be quite limited for both BEA and HEA aircraft, especially if the batteries need to be installed in odd-shaped structures like a wing box. High energy density is therefore an important factor for minimising the required space needed to fit the cells.

Space is quite limited for cars as well especially for cars in the smaller segment. For this reason, most battery electric cars are therefore SUVs as these types of vehicles have sufficient space in the floor thanks to the increased height of the car. Also, smaller A-segment cars, like the Fiat 500 used as reference vehicle for this project, have grown in size compared to their internal combustion engine predecessor to accommodate for the batteries.

Hence the requirement for energy density is set at 925 Wh/L which is the maximum for the HighSpin cells.

#### *4.3.1.3 Voltage range*

The voltage range of the individual cell is directly related to the type of chemistry used. HighSpin aims to find an electrolyte stable at high voltages of up to 5V. The minimum voltage is preferred to be 3,3V.

Since this is the expected voltage range, the cell requirements have been updated accordingly. With the module/pack design, the total number of cells in series required can be calculated by dividing the maximum pack voltage by the maximum cell voltage. The nominal and minimum module/pack voltage can then be calculated by multiplying the given voltages by the number of cells in series.

#### *4.3.1.4 Charge and discharge power*

For both aeronautic and automotive applications, the continuous and peak charge and discharge can affect the performance of the vehicle. For the aeronautical application, the peak power discharge is critical since the power is proportional to the voltage level and discharge current. The cell needs to provide enough power during the take-off and go-around phase to safely complete the mission. Charging power is mainly determined by the type of aircraft and its mission. On the other hand, for the automotive, the peak discharge power is mainly affected by the vehicle acceleration requirements. The charging power is driven mainly by customer requirement for fast charging, as well as -to some extent- energy recuperation from braking/deceleration.

#### *4.3.1.5 Cycle life*

Cycle life is an important factor to the total cost of ownership for passenger cars, vocational vehicles, and aircraft. However, the actual desired number of cycles differs a lot between the three groups.

For passenger cars it was found that a car would need to last at least 1000 cycles, covering a distance of 180 000 km. The WLTC will be used as a reference for the use case of the passenger car. A single WLTC cycle covers a distance of approximately 23.2 km, hence a single test cycle for HighSpin consists of eight WLTC cycles and one charging session to cover a total of 185.6 km per cycle, or 185 600 km over its lifetime.

There is no single ageing profile available for aeronautic applications as this really depends on the application, instead deep cycles are used as a reference. Based on the current state of technology, a cycle life of at least 2000 deep cycles is desired.

#### *4.3.1.6 Calendar life*

Due to the intensive operation of vocational vehicles and aircraft, it is expected that their battery needs to be replaced during their operational lifetime. In contrast, the battery pack of the passenger car is expected to last much longer and thus requires the longest calendar life. It was found that a calendar life for the car is required to be 15 years (@ 30 °C, 100% SOC and 80% of initial capacity).

#### *4.3.1.7 Energy efficiency*

To reduce energy consumption, the round-trip energy efficiency of the cells needs to be as high as possible. In addition, lower efficiencies will result in more heat generated in the battery pack, resulting in higher cooling demands from the thermal management system. The required round-trip energy efficiency should therefore be at least 95%.

#### *4.3.1.8 Cell operating temperature*

The cell operating temperature range needs to be between 0 °C and 45 °C, with an extreme operational temperature range from -25 °C to 55 °C. A thermal management system will be used to optimise temperature window.

#### *4.3.1.9 Maximum allowable self-discharge*

Because passenger cars are sometimes parked for long periods without usage or charging, self-discharge should be as low as possible to prevent the battery from depleting too much when not in use. A maximum of 0.23% per month was specified.

#### *4.3.1.10 Hazard level*

Battery cells are classified as dangerous goods, which can cause safety issues when the cell is transported. The UN 38.3 provides guidance to validate the cell transportability. The UN 38.3 is applicable to all cells regardless of the application and can be found in the UN Manual of Tests and Criteria, test methods and procedures.

Complying with UN 38.3 will ease transport if the cells are produced at a different location than the assembly of the modules and require transportation by air, rail, road, or sea.

### 4.3.2 HighSpin module requirements

The HighSpin module requirements are provided in the tables below. Table 8 lists the safety requirements already discussed in section *3.2 Module safety requirements* with the corresponding DO-311A paragraph number. Next is Table 9 with all other requirements regarding sustainability and mechanical specifications of the containment.

Although most requirements are the same for both automotive and aeronautical applications, there are some differences which will result in two different module designs. These differences evolved mainly from the trade-off between weight reduction and reducing harmful materials.

*Table 8 – List safety requirements from DO-311A*

| Paragraph number | Title |
|---|---|
| | |
| Hardware safety requirements | |
| 2.1.8 | Venting provisions |
| 2.1.10.8 | Electrical Bonding |
| 2.1.10.9 | Dissimilar metals |
| 2.2.1.3 | Insulation resistance |
| 2.2.14 | Handle Strength |
| 2.2.1.10 | Cycling of High Rate Batteries |
| 2.2.1.11 | Rapid Discharge at Short-Time Operating High Temperature |
| 2.2.2.4 | Battery Thermal Runaway Containment |
| 2.2.2.5 | Explosion Containment |
| BMS safety requirements | |
| 2.1.4.2 | Battery Warning Features |
| 2.1.5 | Charging and Discharging Protection |
| 2.1.6 | Overdischarge Protection |
| 2.1.10.2 | Cell Balancing |
| 2.1.10.3 | State of Health function |
| 2.1.10.4 | State of Charge function |
| 2.1.10.5 | Built-In-Test |
| 2.1.10.7 | Prevention from Bus Back Charging |
| 2.2.1.12 | Short Circuit protection |
| 2.2.1.13 | Overdischarge Protection |
| 2.2.1.14 | Overcharge Protection |
| 2.2.2.1 | Short Circuit without Protection |
| 2.2.2.2 | Overdischarge without Protection |
| Environmental safety requirements | |
| 2.3.1 | DO-160<br>Operating low temperature: -45 °C<br>Operating high temperature: +70 °C<br>Altitude (pressure): 7.6 km (37.6 kPa) |

All safety requirements are needed to meet DO-311A compliance. Table 9 below shows the requirements for sustainability and mechanical specification, followed by the rationale for each requirement.

*Table 9 – Module requirements*

| Requirement | Automotive | Aeronautical | Unit |
|---|---|---|---|
| Maximum module voltage | 60 | 900 | V |
| Maximum pack voltage | 750 | 2000 | V |
| Cell-to-Module gravimetric energy density ratio | >80 | >90 | % |
| Module is BMS agnostic | Yes | | |
| Typical minimum charge operating temperature | 0 | 0 | °C |

| | | | |
|---|---|---|---|
| Typical minimum discharge operating temperature | -25 | | °C |
| Typical maximum charge operating temperature | +45 | +70 | °C |
| Typical maximum discharge operating temperature | +55 | | °C |

### *4.3.2.1 Automotive voltage range*

For ease of maintenance, service and disassembly of automotive battery packs, the module must be compliant with voltage class A limits, thus voltage should not be higher than 60V. With a maximum of 5V per cell, this results in a maximum of 12 cells in series.

The maximum pack voltage is expected to be 400V for passenger cars and up to 750V for electric vocational vehicles.

### *4.3.2.2 Aeronautical voltage range*

The module voltage range for aeronautical applications depend mainly on the total amount of modules. For example, the Velis electro has two packs that both consist of one ‘module.’ In this case, each module must provide the full required voltage range needed for the aircraft since they are not allowed to be put in series for redundancy – in case one module fails, the entire string cannot be used anymore resulting in total loss of power, with two modules in parallel one module could fail while the other module can still deliver sufficient power for the aircraft to land safely.

The total pack voltage is expected to be 2000V for larger aircraft with multiple modules in series to form a pack, and multiple packs in parallel for redundancy to prevent total loss of propulsion when one module fails.

### *4.3.2.3 Cell to module gravimetric energy density ratio*

The cell to module gravimetric energy density ratio, also known as packaging efficiency, needs to be as high as possible for both automotive and aeronautical application. However, the main trade-off is sustainability since lighter materials – such as carbon fibre composites in particular – are harder to recycle and cause more CO2 emissions than other materials.

Because weight is more problematic for aircraft than for automotive, and because the total number of aircraft produced is quite low compared to for example the number of passenger cars and lorries, it seems acceptable to use hard-to-recycle materials in order to reduce the battery pack weight on the condition that component reusability for the aeronautical battery packs is increased.

### *4.3.2.4 Module is BMS agnostic*

The aeronautic modules shall be BMS agnostic to prevent vendor lock-in and to keep the option open for alternative or in-house developed BMS. The automotive modules were already designed in the predecessor project to accommodate a certain BMS board.

### *4.3.2.5 Typical operating temperatures*

Based on DO-160 (Category B2), the minimum and maximum operating temperatures for aeronautical application are -45 to +70 °C.

For automotive the minimum and maximum operating temperatures for charging are 0 to +45 °C and between -25 and +55 for discharging.

# 5 SUSTAINABILITY REQUIREMENTS

The whole value chain of battery manufacturing, from raw materials extraction through cell assembly, module integration, use in first and possibly second life, and finally recycling, can have significant impacts in environmental and social dimension. It is therefore particularly important that the design of cells and modules for both automotive and aeronautical applications considers measures to reduce critical material use, improve manufacturing processes, extend overall useful life by enhancing usability and efficiency, but also recyclability and second-life potential, to reduce the negative impacts of batteries on the environment and society as much as possible.

Sustainability requirements relating to the battery within the scope of the HighSpin project were brainstormed and widely discussed within a three-part Eco Design Workshop organized by CEA and held in November 2022 (part 1), February 2023 (part 2) and March 2023 (part 3). All sustainability requirements and workshop conclusions will be summarised in a separate document, which will be a co-applicable document for the sustainability considerations in addition to what is written in the present D1.3.

In the present document, the focus is on the following main topics: cycle life improvement, and end of life processing.

## 5.1 CYCLE LIFE IMPROVEMENT

To improve the cycle life of cells it is necessary to know what contributes to increased cell degradation. For traditional li-ion chemistries these are:

- Cycling at extreme temperatures
- Deep cycles
- High C-rates

Since HighSpin aims to develop cells with a LNMO/Si/C chemistry and a novel electrolyte, tests will have to be performed to determine to what extent the above conditions contribute to cell degradation. In addition, it should be investigated if other factors not mentioned above have a negative effect on cycle life as well to get a clear picture of all aspects that affect cycle life.

### 5.1.1 Cycling at extreme temperatures

If cycling at extreme temperatures proves to have a negative effect on cell cycle life, a strategy to limit the effect of extreme outside temperatures should be examined, such as but not limited to an adequate thermal management system.

Passive cooling could be a good solution when heat generated by the cells can be dissipated to (cooler) outside air. When operating in extreme hot temperatures, an active thermal management system might be needed with a heat pump and additional insulation material to reduce the rate at which the pack is heated by the environment. Additional insulation material might be useful as well when operating in extreme cold conditions to reduce the need for heating.

### 5.1.2 Deep cycles and high C-rates

An important research question for the used combination of materials in LMNO/Si/C cells is how cycle life is affected by deep cycling and high C-rates. The optimum DoD will likely be a trade-off between cycle life and capacity, and can be different for automotive and aeronautical applications.

The DoD is already significantly reduced for aeronautical application to ensure sufficient energy for emergency go-around. This should already improve cycle life of the cells. Next step would be to optimise the maximum charging voltage based on the flight plan to prevent fully charging the cells for short flights.

## 5.2 END OF LIFE EXTENSION

Finally, increasing cycle life could be achieved by reusing the battery for other applications where a lower capacity (or actually: a lower specific energy, as multiple batteries can be stringed together to increase capacity) is acceptable. In general, the EOL of a battery is defined at 80% of the BOL capacity. This means that even at EOL, there is still 80% of the original capacity left.

When reusing isn't possible, recycling becomes the most important aspect, for which design for dismantling and a battery passport are essential to efficiently recycle the pack, which are both discussed in paragraph 5.3.1 and 5.3.2 respectively.

## 5.3 END OF LIFE PROCESSING

### 5.3.1 Design for dismantling

Design for dismantling, also known as design for recycling or design for disassembly is a way to design the battery modules that improve the separation of components and materials for recovery and recycling.

Aviation in general prefers to use fasteners, such as bolts, over glue as fasteners are much more predictable for stress analyses and provides a visual check to see if it is secured correctly. Hence similar fasteners are intended to use for the battery pack which should ease disassembly at the end of life to improve reusing/recycling.

There are unfortunately also a couple of harmful materials, most notably carbon fibre. Despite its very energy-intensive production process and very poor recyclability, it is unlikely to replace it for a different, less harmful, material. The main advantage of carbon fibre is its strength-to-weight ratio. Replacing the carbon fibre would increase the EOW and, as the MTOW remains the same, reduces the payload.

### 5.3.2 Battery passport

To facilitate the decision about whether a battery is useable for a second life or for recycling, at EOL it is useful to know several things about its content and condition, including but not limited to material content, aging profile, state of charge and general safety condition, etc. This can help to reduce the cost of reconditioning and/or recycling. To such ends, the concept of a battery passport has been in development for several years. One leading global effort is the Battery Passport by the Global Battery Alliance [7]. At time of writing the Battery Passport Greenhouse Gas Rulebook was in its version

1.4, and first Battery Passport pilots with partial data were available online. The development in this domain is ongoing, and the consortium will monitor the development of this and other relevant sustainability standards for batteries to guide its work where it comes to eco-design and lifecycle analysis.

# 6 CONCLUSION

The present deliverable D1.3 consolidated the automotive requirements and aeronautical requirements provided in deliverables D1.1 and D1.2, respectively. This forms a comprehensive document with all safety and performance requirements, as well as some sustainability requirements. The latter will be supplemented in a separate (internal) HighSpin document, and all requirements together will function as input for WP2 and WP5 and finally for the validation/verification in WP6.

A brief overview of the chosen reference vehicles was provided in section 2. For automotive this is a small passenger car and a lorry, both fully electric. For aviation this is a small fully electric two-seater aircraft and a hybrid hydrogen-electric commuter aircraft for up to 19 passengers.

Section 3 gives the safety requirements on cell level and module level. It was found that the cell level requirements are mainly focused on the transportability of the cells during production and thus only require to comply to UN38.3 while the safety requirements needed for operation of the battery pack are on module level.

Finally, the performance requirements have been consolidated in section 4. Starting with a recap of the results from *D1.1 Automotive requirements* in section 4.1 and from *D1.2 Aeronautical requirements* in section 4.2, the requirements have been merged together in section 4.3 for the HighSpin project. The requirements for automotive and aeronautical application are identical on cell level (the more stringent of the two have been selected for testing purposes), but on module level there are some slight differences. More detailed module-level requirements will furthermore be developed in HighSpin WP5.

Regarding sustainability aspects, this deliverable focused on cycle life improvement as a focus of research from a testing perspective that can be performed in WP6 (e.g., extreme temperatures, depth of discharge, c-rates). We have also referenced Action Partnerships of the Global Battery Alliance, such as the Battery Passport or first data pilots, as global efforts to facilitate reuse of batteries, and to monitor and use as a (non-exhaustive) guide to considering sustainability aspects along the battery value chain.

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