Requirements for automotive application

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 to 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 delivers 390 Wh/kg and 925 Wh/l target energy density, 790 W/kg and 1,850 W/l target power density (at 2C), 2,000 deep cycles, and 90 €/kWh target 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 laser structuring 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 will be demonstrated, 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.

Further information about the project can also be found here: https://cordis.europa.eu/project/id/101069508.

LIST OF ABBREVIATIONS

Acronym / Short Name	Meaning
AC	Alternating Current
BEV	Battery Electric Vehicle
BMS	Battery Management System
BOL	Beginning of Life
BP	Battery Pack
CD	Charge Depletion
DC	Direct Current
DOD	Depth of Discharge
EOL	End of Life
EPA	Environmental Protection Agency
GHG	Greenhouse Gas Emissions
kWh	Kilowatt-hour
ICE	Internal Combustion Engine
NEDC	New European Driving Cycle
OEM	Original Equipment Manufacturer
PHEV	Plug-in Hybrid Electric Vehicle
RMS	Root Mean Square
SOC	State of Charge
SOE	State of Energy
SOH	State of Health
WLTC	Worldwide Harmonized Light Vehicles Test Cycle
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
WP	Work Package

EXECUTIVE SUMMARY

To develop battery cells suitable for automotive and aeronautic applications, HighSpin takes the requirements of these applications as a starting point. The requirements of each application are first analysed in detail and separately from each other, then (in subsequent project steps) merged to find a common set of battery requirements between automotive and aeronautic applications. The present document examines the automotive requirements. It builds on requirements defined in the predecessor project 3beLiEVe, almost three years ago.

For the selection of reference vehicles for which requirements are considered, the plug-in hybrid electric vehicle (PHEV) included in 3beLiEVe is dropped, given that PHEVs are projected to play a subordinate role in the European market, and due to the questionable contribution of PHEVs in terms of GHG reduction. The vehicles remaining in the selection are the Fiat 500 electric, as a reference vehicle in the A-segment, as well as the Volvo FL electric as representative for a vocational (urban duty) vehicle with multipurpose configurability. The battery-pack level requirements for these vehicles were updated by reviewing the latest editions of these vehicles as available on the market in late 2022. This resulted in a doubling in the minimum battery size for the truck, from formerly 100 kWh to now 200 kWh, and in an increase from two to three for the minimum number of packs with which this vehicle is operated. For the A-segment BEV, the pack size could in fact be slightly decreased from the original requirement of 50 kWh to 42.2 kWh. This on one hand is related to design choices about the example battery pack design that is used to obtain requirements at cell level, and on the other hand done with a view to eco-design and resource efficiency considerations, to avoid over-dimensioning of the battery packs where possible.

The performance categories in which requirements are defined were narrowed down from those of 3beLiEVe, dropping requirements in the mechanical and performance categories, as design and testing for such kind of requirements (arising mainly on pack level) are out of scope for HighSpin. This leaves the focus for testing on the electrical (battery performance) and thermal (operation and storage) requirements.

Using known cell and battery designs from 3beLiEVe, hypothetical battery packs that meet the cornerstone energy and voltage requirements for the two vehicles were designed. These designs were used to translate the vehicle requirements, given at pack level, down to the module and cell level. The derived requirements on cell and module level for the A-segment vehicle and the urban truck were then merged, selecting in each case the more stringent of the two requirements. With the assumed pack designs and cell specifications, the C-rates that individual

cells should see range from 2.8C (relative to installed capacity) 3.2C (relative to useable capacity) in discharge, and from 3.6C to 3.9C for charging (again for installed and useable capacity, respectively). The temperature requirements relating to operation and storage have remained unchanged.

1 INTRODUCTION

The battery materials and cells in the HighSpin project are developed with a view to automotive applications and will be subjected to testing on the cell and module level (no full battery pack or vehicle integration). To obtain requirements on the cell and module levels, the HighSpin project takes the vehicle-level requirements from its predecessor project 3beLiEVe. The set of vehicles selected as a source of requirements is re-examined and updated. Likewise, the requirements of the updated vehicle set, as well as the performance categories are revisited and updated. Then, a battery pack architecture capable of meeting the updated requirements of each selected vehicle is formulated using the 3beLiEVe module design. The updated vehicle (battery pack-level) requirements are then broken down against the proposed pack architectures to obtain cell- and module level requirements, which are given in section 3.4.

Overall, the approach to obtaining the cell- and module-level requirements is depicted in Figure 1.

Figure 1: Methodological approach to generating the automotive requirements for HighSpin at cell and module level

For background and comparison, the interested reader may also refer to D1.1 Consolidated requirements for the 3beLiEVe battery pack. Since this is a public deliverable that describes some of the background considerations for the selection of criteria and requirements, these are not repeated in the present document.

The requirements in the present D1.1 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 for cycle life, energy density and power density that are application-agnostic. In this project, the bottom-up values for automotive (D1.1) and aeronautic (D1.2) 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 global top-down values in the testing and evaluation phase. The global top-down KPIs are in any case preserved.

Figure 2 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.

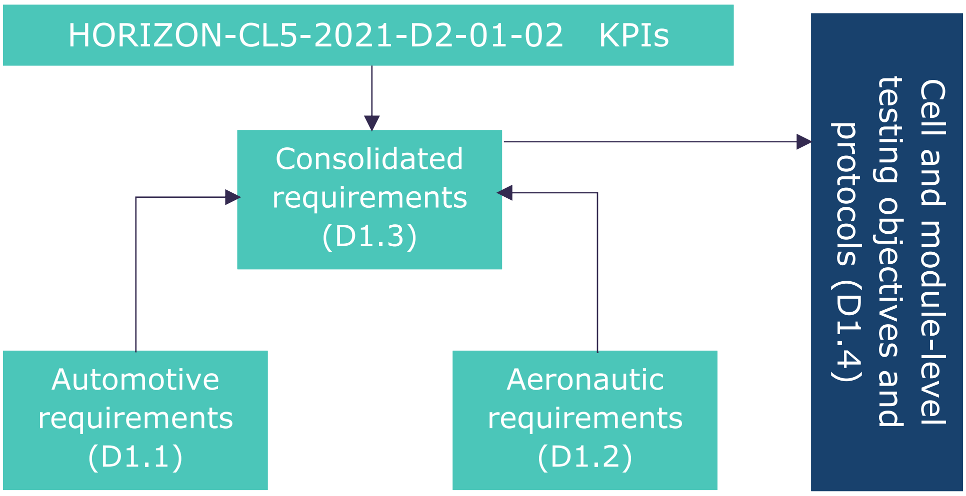


Figure 2: Relation of requirements

2 UPDATES

2.1 METHODOLOGY

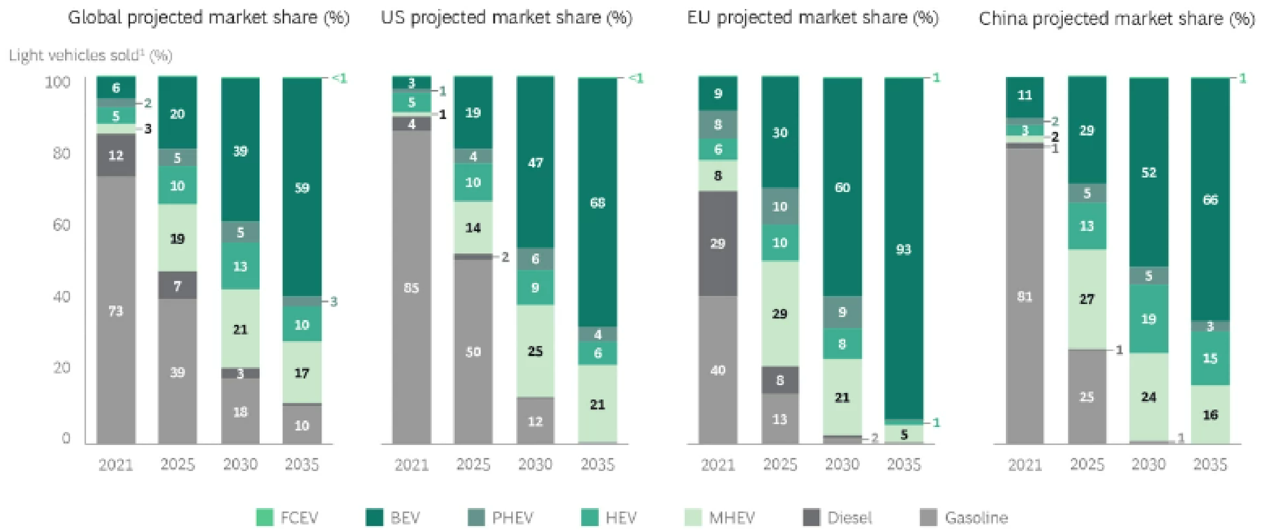
The automotive requirements as defined in HighSpin's predecessor project, 3beLiEVe, are the starting point for the definition of automotive requirements for HighSpin. From this basis, we consider whether the set of vehicles used as a source of requirements is still up to date. This is discussed in section 2.2.

Section 2.3 describes the rationale behind updates to the set of performance categories (e.g. electrical, mechanical, thermal, etc.). Section 2.4 reviews whether the requirements for the selected vehicles need updating, e.g., due to substantial changes in the state of the art in the period since the publication of the 3beLiEVe requirements (e.g. larger or smaller battery packs). To assess this, we look at the specifications of the vehicles selected/confirmed in section 2.2 as available on the market at time of writing.

2.2 VEHICLE SELECTION

3beLiEVe considered two reference vehicles for the passenger vehicle category: a City car BEV (Segment A/B, Fiat 500) and a C-segment PHEV (Fiat 500X). As a vocational vehicle, the VOLVO FL Electric 16-tonne truck served as a reference platform.

In HighSpin, for the passenger vehicles, the C-segment PHEV is dropped. The rationale for this is that according to market forecasts (Figure 3), PHEVs will play only a subordinated role in terms of market share in Europe by 2030 and beyond. Furthermore, by definition these include a combustion engine, whereas the continued use of fossil fuels in transport is not compatible with the rapid and deep decarbonisation needed in the transport sector to meet the 1.5°C or even 2°C target of the Paris Agreement. In this light, passenger PHEVs appear obsolete as a reference platform and are therefore out of scope for HighSpin.



Source: BCG analysis.

Note: FCEV = fuel cell electric; BEV = battery electric; PHEV = plug-in hybrid electric; HEV = full hybrid electric; MHEV = mild hybrid electric. Because of rounding, the percentage total for a particular year may not equal 100%.

[1]Forecast includes cars, SUVs, and all other light vehicles except heavy vans.

Figure 3: Market share of powertrain types over time in different geographical regions [1].

This down-selection leaves two vehicles as reference platforms against which to articulate automotive requirements in HighSpin: the Fiat 500 electric, and the VOLVO FL Electric (Figure 4). 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 4: Reference vehicles for requirements: passenger vehicles - city car BEV (Segment A/B, Fiat 500; vocational vehicles - VOLVO FL Electric (image source: electrive.net)

2.3 PERFORMANCE CATEGORIES

3beLiEVe demonstrators and testing were designed to go from cell level all the way to a small battery pack. Accordingly, a wide set of performance categories was considered in the specifications. Here we examine which of the categories are needed for the narrower demonstrator scope (only up to module level) for HighSpin.

The vehicle requirements in 3beLiEVe were grouped into the following categories:

- battery performance
- mechanical
- thermal
- connectors and BMS
- additional information.

With regard to **battery performance**, desired values for energy [kWh], voltage [V], power [kW], current [A], application performance, life expectation, and round-trip efficiency have been considered (Table 1). Since these are all relevant and can be broken down to cell level, all categories are kept for HighSpin.

Battery Performance	**Energy [kWh]**
	Voltage [V]
	Power [kW]
	Current [A]
	Application Performance
	Life Expectation
	Round trip efficiency

Table 1: Battery Performance parameters

Regarding mechanical aspects, volume, weight, structural properties, and performance specifications have been examined (Table 2). Since module and pack designs made in 3beLiEVe already factored in the mechanical requirements, this latter category will be ignored completely for HighSpin, as the project will use the automotive module design developed in 3beLiEVe on one hand, and on the other hand will not perform pack-level testing at all. For pack level, simulation of the full pack size is expected to be done at the test bench e.g. using a hardware-in-the-loop approach to virtually scale the physical demonstrator to the required size. Thus, no new mechanical requirements for automotive will be formulated. Instead, the mechanical designs for cell and module from 3beLiEVe will be adopted.

Mechanical	**Volume**
	Weight
	Structural
	Structural Performance

Table 2: Mechanical parameters description

For thermal requirements, operating conditions and storage conditions have been contemplated. These remain relevant for HighSpin and are likewise kept (Table 3).

Thermal	**Operating Conditions**
	Storage Conditions

Table 3: Thermal parameters description

Connector and BMS-related requirements also are ignored in HighSpin, since these, too, were already specified in 3beLiEVE and will be reused as needed (Table 4).

Connectors	
BMS	**Communication**
	Additional

Table 4: Connectors and BMS parameters description

2.4 VEHICLE SPECIFICATIONS

To assess whether an update of the requirements for the selected vehicles (section 2.2) is needed, we look to the market to determine whether the specifications of the currently available vehicle models –especially with regard to the characteristics of the battery packs– are comparable to those specified in the 3beLiEVe requirements over two and half years ago.

2.4.1 Passenger vehicles

For passenger vehicles, to determine what electric vehicles are currently available on the market, we looked to the German ADAC e-cars overview [1]. This shows that the Fiat 500e (electric) is available in four editions, which vary chiefly in battery size, range, and maximum speed (Table 5). The minimum installed gross battery capacity is 23.8 kWh (21.3 kWh net; 89.5% of gross capacity) and the maximum is 42 kWh gross (37.3 kWh net; 88.8%). The nominal energy at beginning of life specified in the 3beLiEVe requirements was 50 kWh gross (45 kWh net; 90%), in other words a larger battery size with a slightly higher share of usable energy at BoL. The gross nominal energy of the 3beLiEVe requirement is thus 119% of the largest gross energy content of the currently available model with the largest battery size.

Table 5: Fiat 500 electric models available on the German market in 2022.

Model	**Range (km)**	**Power (kW)**	**Vmax (km/h)**	**Battery– net (kWh)**	**Battery – gross (kWh)**
500e (23,8 kWh)	190	70	135	21.3	24
500e (42 kWh)	321	87	150	37.3	42
500e 3+1 (42 kWh)	314	87	150	37.3	42
500e Cabrio (23,8 kWh)	190	70	135	21.3	24
500e Cabrio (42 kWh)	320	87	150	37.3	42

2.4.2 Vocational vehicle (16-tonne truck)

For VOLVO the targeted vehicle is a 16-ton full electric distribution truck, specifically the Volvo FL Electric. The FL Electric is designed for urban delivery and communal service with an electric range up to 300 km. The truck has an electric motor with a top performance of 185 kW, and a regular performance of 130 kW. Energy storage will be covered by three to six lithium-ion battery packs. Previously in 3beLiEVe, the energy content was specified as 100 to 300 kWh.
We queried the Volvo Trucks website for the From the truck’s technical data, we can see that it is a vehicle that can be customized for different uses (e.g., goods transport, garbage collection, etc.) based on a chassis that can be equipped with different mounts. Compared to the 3beLiEVe energy content specification of 100 – 300 kWh energy content for the truck’s battery, we can see the present requirements have increased to 200 – 395 kWh with three to six battery packs (Table 6).

Table 6: Volvo FL Electric - selected technical specifications

Vehicle properties	**Volvo FL Electric**
Gross traction mass	Up to 16.7 tonnes
Battery capacity	200–395 kWh, 3–6 batteries
Range	Up to 300 km
Duration of charging procedure (full charge)	11 h with AC (22 kW)
	2 h with DC (150 kW)
Propulsion	Single electric motor, 2-speed transmission
Power	Up to 130kw (174hp) I continuous

3 REQUIREMENTS

3.1 METHODOLOGY

The updates to the vehicle selection and their market specification (regarding battery pack) performed in the section 2 are used here to update the battery-pack level requirements already established in 3beLiEVe. The resulting pack-level requirements for both vehicles are given in section 3.2.

These pack-level requirements need to be broken down to the functional units (modules and cells) that will be tested in HighSpin WP6, since the electrical layout of the battery packs will have an impact on the voltages and currents that individual cells will “experience”, i.e. the pack design impacts the cell- and module-level requirements. Accordingly, in section 3.3 we take the pack-level requirements and build packs that satisfy these requirements, using cells and modules of 3beLiEVe specification as building blocks. It is against these resulting pack architectures that the requirements on module and cell level are derived. These, as final results of this exercise, are given in section 3.4.

3.2 BATTERY-PACK (VEHICLE) LEVEL

3.2.1 Passenger car

The original 3beLiEVe requirements quoted a value of 50 kWh nominal energy (installed capacity) at BOL, reducing this by 10% to obtain usable energy at BOL, and considering that the battery reaches the End of Life (EOL) condition when only 80% of initial usable energy is still available. Or, bottom up: for city car BEV the 36 kWh of usable energy requested at the EOL corresponds to 45 kWh of usable energy at the Beginning of Life (BOL). Considering that in section 3.3.2, the proposed pack design can achieve either slightly more or slightly less than, but not exactly the requested 50 kWh nominal energy at BOL, and that for eco-design reasons we have opted to slightly undersize the pack design, the actual values used are given in brackets in Table 7.

Furthermore, and unchanged from 3beLiEVe: for this application, the usable SOC window amounts to 90% and ranges from 95% to 5%. For the battery system, the desired voltage range is 300-400 V for full performance, and 260-400 V for reduced performance; for the modular pack, the maximum module voltage has to be not higher than 60 V DC to be compliant with voltage class A limits (maintenance, service and easy disassembly for second life and/or recycling).

Peak Discharge Power (10s) at BOL is requested to be 100 kW (10s power required at 40% SOC at temperatures between 25° and 50 °C) and continuous discharge power at BOL is requested to be 70 kW.

Continuous charge - plug-in charging power is requested to be 22 kW (@380 V / 32 A).

The estimated pack RMS power is 8 kW, from the average of NEDC and WLTC Class 3 Duty cycles.

The requested energy throughput before EOL is 38 MWh, entirely coming from charge depleting mode.

Calendar life is required to be 15 years (@ 30 °C, 100% SOC and 80% of initial usable capacity).

Target weight for the battery pack is 300 kg, and structural performance regulations are based on UN-ECE R100 – although this requirement is not considered in HighSpin.

Operating temperature range is requested to be -25 - 55 °C for discharge, and 0 - 45 °C for charge. Storage temperature range is requested to be -20 - 55 °C. These requirements are summarised in Table 7.

Table 7: Requirements for City car BEV – segment A/B

Specifications / Requirements	Desired Values
Host Application / Battery Type	BEV (Segment A/B)
Nominal Energy at Beginning of Life (Battery System)	42.2 kWh[1]
Usable Energy at Beginning of Life (Battery System)	38.0 kWh | 90% of nominal
Usable Energy at End of Life (Battery System)	30.4 kWh | 80% of usable
Nominal Voltage (Battery System)	350-360 V
Voltage Range - Full Performance (Battery System)	300 to 400 V
Nominal and Voltage Range (Modular Pack)	<60 V
Peak Discharge Power (2 s) - BOL	120 kW
Peak Discharge Power (10 s) - BOL	100 kW
Continuous Discharge - BOL	70 kW
Peak Charge Power (2 s) - BOL	150 kW
Peak Charge Power (10 s) - BOL	120 kW
Continuous Charge - BOL	100 kW
Continuous Charge - Plug-in Charging	22 kW (@380 V / 32 A)
Continuous Charge - Fast Charge - SOC range and time	100 kW
Maximum current (10s)	350 A
Maximum current in charge (10s pulse)	400 A
Duty cycles	WLTC Class 3
	Proprietary OEM cycle (usage pattern)
Expected No. of Cycles / Range in Charge Depletion Mode	1000 cycles / 90% SOC 38 MWh

[1] Originally 50 kWh - see explanation in section 3.3.2

Soc Window (Range before EoL)	5% - 95%
End of Life	80% of initial usable capacity
Calendar Life	15 years
Typical Operating Temperature - Discharge (min, max)	-25 to 55 °C
Typical Operating Temperature - Charge (min, max)	0 to 45 °C

3.2.2 Vocational vehicle

For the vocational vehicle the nominal operating voltage range is 600 V. The desired battery should fulfil the power requirement of the electric machines installed in the vehicle. Usually, a single battery pack hardly fulfils the requirements of the vehicle; therefore, multiple battery packs are generally needed for commercial electric vehicles.

Table 8 shows the requirements for the Volvo 16-tonne truck, updated with the 200-395 kWh nominal energy requirement and the charging durations from Table 6, but otherwise unchanged from the 3beLiEVe requirements.

Table 8: Requirements for 16-tonne track (see also Annex 1)

Specifications / Requirements	Desired Values
Host Application / Battery Type	EV (Volvo truck FL 16 tons)
Nominal Energy	200-395kWh
Nominal Voltage (Battery System)	600V
Voltage Range - Full Performance (Battery System)	500-750V
Nominal and Voltage Range (Modular Pack)	<60V
Continuous Discharge - BOL	100-130kW
Continuous Charge - BOL	22kW(AC)/150kW(DC)
Duration of charging procedure (full charge)	11 h with AC (22 kW) 2h with DC (150 kW)
Duty cycles	2 h with DC (150 kW)
Expected No. of Cycles / Range	>5000
End of Life	80% of initial usable capacity
Calendar Life	8-10 years
Extreme Storage Temperatures (min, max)	-30 to 60°C

An example of the dynamic cycle for the commercial vehicle is shown in the figure below. This cycle will be the reference point for estimating the lifetime of the pack for the commercial vehicle specified above. Practically, lifetime of the pack would be estimated from the testing on the cell level using this dynamic cycle with downscaling of the current profile according to the cell specification.

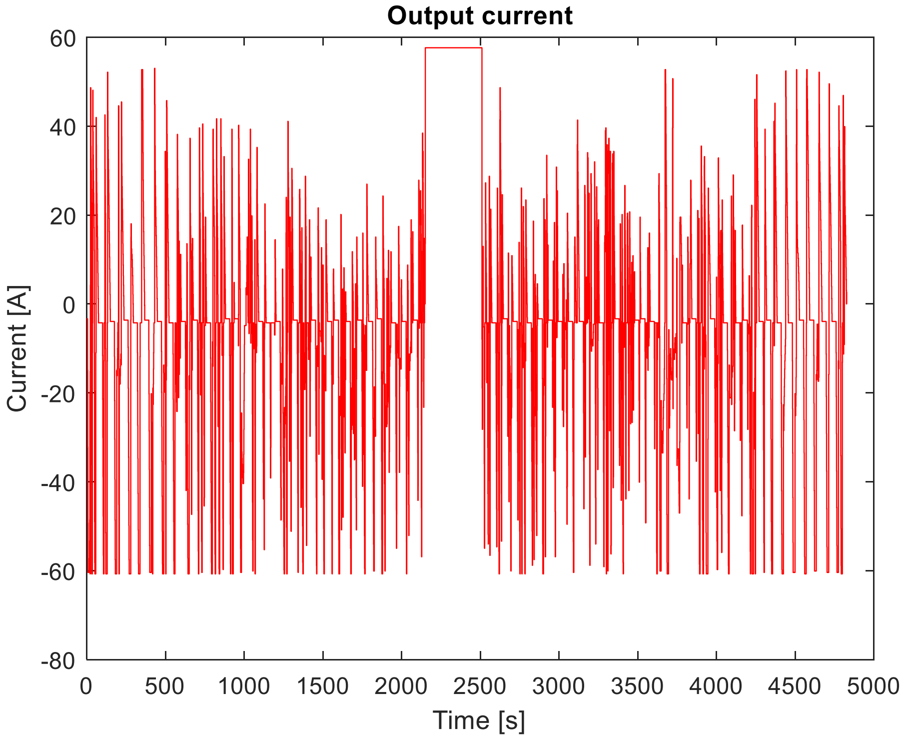


Figure 5: Simulated dynamic driving cycle to current profile for Volvo application

3.3 BATTERY PACK ARCHITECTURES USING THE 3BELIEVE MODULE

Demonstrator testing in HighSpin for the automotive applications will be performed on cell and module level only. Pack assembly and testing are not in scope of the project. However, since vehicle requirements are given on pack level, to make these operational for HighSpin, the pack-level requirements need to be translated to the module and cell level. To do this, a target architecture that is composed of automotive module building blocks to be used in HighSpin must be considered for both vehicles.

Conceivable target architectures are constructed using the battery module as a building block. The focus is on electrical requirements; mechanical constraints are neglected as their consideration is not the focus of this project.

3.3.1 Battery module architecture

The automotive module specification of 3beLiEVe from an electrical perspective is such that a set of 8 (eight) pouch cells are electrically connected in series in one string; there are no further parallel strings in the module, hence: 8S1P. The module will be used as the basic building block from which to construct (theoretical) packs to meet the requirements on vehicle level.

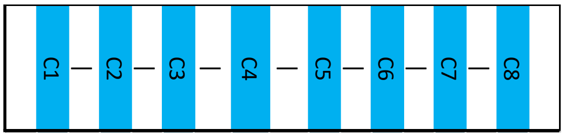


Figure 6:Battery module architecture, 8S1P electrical arrangement: 8 cells (C1-C8, marked in blue)

The target specification for the cells to be integrated in the module is known from 3beLiEVe and is given in Table 9.

Table 9: LNMO cell electrical characteristics

Cell	**Value**	**Unit**
Cell maximum voltage	4.9	V
Cell nominal voltage	4.4	V
Cell minimum voltage	3.5	V
Cell capacity	30	Ah
Cell nominal energy	132	Wh

Based on the known cell characteristics, the specifications of the module are given in Table 10.

Table 10: Module electrical specifications

Module	**Value**	**Unit**
# cells (in series)	8	cells
Maximum voltage	39.2	V
Nominal voltage	35.2	V
Module capacity	30	Ah
Module nominal energy	1056	Wh

3.3.2 Battery pack architecture for passenger vehicle

To obtain a battery pack composed of 8S1P modules that can meet the basic electrical and energy requirements for the passenger vehicle, we begin with two considerations. First, what is the number of modules that are needed in series to obtain the required voltage profile, and second, what are the total number of modules needed to obtain the target energy content?

Given the module's maximum voltage of 39.2V and nominal voltage of 35.2V, we consider that 10 to 11 modules are needed in series to obtain the 400V requested for full performance (cf. Table 7). Here we opt for 10 modules in series to avoid exceeding 400V.

Next, we address the energy content. This is done by adding parallel strings of modules (10 apiece). Five parallel strings of 10 modules each gives a gross energy content of 52.8 kWh (installed) and 47.5 kWh (useable), whereas four parallel strings give 42.2 kWh and 38.0 kWh, respectively. We opt for the latter configuration of four parallel strings, given that the resulting energy content is well inside the envelope of A-segment vehicles on the market today (cf. Table 5), and considering also that an oversized pack with five strings would represent a greater ecological burden from a production perspective, with accordingly a longer break-even time in terms of cycled energy and avoided emissions. The resulting pack configuration, then, is given in Table 11.

Table 11: Proposed battery pack configuration for A-segment BEV

BEV A-Segment Pack	**Value**	**Unit**
# modules in series	10	modules
# modules in parallel	4	modules
Maximum voltage	392	V
Nominal voltage	352	V
Energy content (installed)	42.24	kWh
Useable energy limitation	90	%
Energy content (useable)	38.0	kWh
# cells in pack	320	cells
# cells in series	80	cells

3.3.3 Battery pack architecture for vocational vehicle

To obtain a suitable pack architecture for the urban truck, we proceed in a similar fashion as for the passenger vehicle.

To obtain a maximum voltage in the range of 500-750V and a nominal voltage around 600V (cf. Table 8), 17 modules in series are suitable.

From Table 6 we know the truck runs on 3-6 batteries (packs) and has a battery (pack) capacity of 200-395 kWh. We may therefore deduce that one pack has around 65 kWh. To obtain this energy content with our module, we can specify 4 parallel strings, each with 17 modules in series. This results in just under

65kWh useable energy content per pack and in an overall proposed pack architecture for the urban track as given in Table 12.

Table 12: Proposed battery pack configuration for urban electric truck

Electric Truck Pack	Value	Unit
# modules in series	17	modules
# modules in parallel	4	modules
Maximum voltage	666.4	V
Nominal voltage	598.4	V
Energy content (installed)	71.808	kWh
Useable energy limitation	90	%
Energy content (useable)	64.6	kWh
# cells in pack	544	cells
# cells in series	136	cells

To obtain the lower end of the energy content (~200 kWh), we propose to put three packs as per Table 12 in parallel electrical connection. To obtain the top end of the energy content specification (395 kWh), the configuration can simply be doubled by placing another three packs in parallel alongside the first three.

3.4 MODULE AND CELL-LEVEL REQUIREMENTS

Having defined battery pack architectures that can meet the requirements at vehicle level, it is now possible to scale the vehicle/pack-level requirements down to a module and cell level. This is done by considering what current and voltage each cell and module will see as a function of i) the requirement and ii) the pack architecture to which that requirement is applied. The resulting values are given in the Annex for both the passenger vehicle and the urban truck.

In a next step, we attempt to consolidate the resulting cell- and pack-level requirements from both vehicles (given in the Annex) wherever possible. That is, for each performance category where requirements for both the passenger vehicle and the truck are given, we take on the cell/module level the more demanding value. Table 13 gives these resulting automotive requirements on cell and module level. Where C-rates are indicated, these are relative to the specification of the cell given in Table 9: LNMO cell electrical characteristicsTable 9.

Since we did not have power profiles for the automotive applications, we propose to obtain these via the usage profile (e.g. WLTP class 3) and the target vehicle characteristics (e.g. mass, front cross-sectional area), e.g. in a hardware-in-the-loop test bench setup or by determining them through offline simulation or other means.

Table 13: Combined requirements from passenger and vocational vehicle, at cell and module level

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
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	C-rates rel. to installed and useable capacities: 2.8C – 3.2C
Peak Discharge Power (10 s) - BoL	[kW]	0.31	2.5	2.4C – 2.6C
Continuous Discharge - BoL	[kW]	0.22	1.75	1.7C – 1.8C
Peak Charge Power (2 s) - BoL	[kW]	0.47	3.75	3.6C – 3.9C
Peak Charge Power (10 s) - BoL	[kW]	0.38	3	2.8C – 3.2C
Continuous Charge - BoL	[kW]	0.313	2.5	2.4C – 2.6C
Peak Discharge Power and Duration (2s) - EoL	[kW]	0.30	2.4	2.3C – 2.5C
Peak Discharge Power and Duration (10s) - EoL	[kW]	0.25	2	1.9C – 2.1C
Continuous Discharge - EoL	[kW]	0.175	1.4	1.3C – 1.5C
Peak Charge Power and Duration (2s) - EoL	[kW]	0.375	3	2.8C – 3.2C

Peak Charge Power and Duration (10s) - EoL	[kW]	0.300	2.4	2.3C – 2.5C
Continuous Charge - EoL	[kW]	0.250	2	1.9C – 2.1C
Continuous Charge - Plug-in Charging	[kW]	0.069	0.55	0.5C – 0.6C
Continuous Charge - Fast Charge - SoC range and time	[kW]	0.313	2.5	For 1500 s 2.4C – 2.6C
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. **= 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	-25 to 55 °C		
Extreme Operating Temperatures (min, max)	°C	-30 to 60 °C		Optional
Storage Temperature (min, max)	°C	-20 to 55 °C		
Max Allowable Self Discharge (Wh/month)	Wh/ month	0.31	2.5	

4 CONCLUSIONS

The vehicles selected as reference platforms for derivation of battery requirements in the 3beLiEVe project in 2020 were reviewed, and for passenger vehicles narrowed down to battery electric vehicles (BEVs) only, while dropping plug-in hybrids (PHEVs) due to their subordinate role in market projections for Europe and their questionable contribution to significant GHG emissions reductions.

For the vehicles remaining in the selection -the Fiat 500 electric and the Volvo FL electric truck- their latest specifications (as available on the market in late 2022) were reviewed with respect to the dimensioning of their battery packs. Based on these updated specifications, the requirements for the same vehicles already available from 3beLiEVe were updated. Effectively this resulted in only minor changes, notably an upsizing of the minimum battery pack size for the truck, and -counterintuitively- a downsizing of the battery pack size for the Fiat 500 electric.

Finally, using the 3beLiEVe battery module specification as the basic building block, a battery pack architecture capable of meeting the updated requirements of each vehicle was proposed. Against this architecture, the vehicle (battery pack) requirements were translated down to cell and module level to obtain operational values (requirements) against which testing can be performed in the HighSpin project. The values obtained both from the vehicle and the truck were merged into a combined set of cell- and module-level requirements, where the more demanding of the two was selected. Power profiles were not directly available. To obtain these we proposed translating driving cycles (e.g. NEDC or WLTC), given known values for key vehicle properties.

With the proposed architectures and dimensioning of the packs, the pack-level voltage and capacity requirements can be met, and the highest C-rates (on cell level) for discharging amount to 2.8C – 3.2C and are in the range of 3.6C – 3.9C for charging, albeit for short periods of time. These, together with the cycle life, are expected to be some of the main challenges to be overcome on a cell level. The wide range of operating and storage temperature conditions have remained unaltered and pose an additional challenge to the performance of the battery cells over their lifetime.

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Annex – Vehicle-level requirements broken down to module and cell level

A-Segment BEV - VEHICLE (Full pack)				Cell			Unit	Module		
Subtopic	**Specifications / Requirements**	**Desired Values**	**Note**	**Min**	**Nom**	**Max**		**Min**	**Nom**	**Ma**
Energy [kWh]	Nominal Energy at Beginning of Life (Battery System)	42.2	BoL energies (installed and usable) to satisfy the desired EoL usable energy considering a CD SoC window of 90% (from 95 to 5%) for usable energy and a loss of capacity of 20% from usable initial one on the life	-	0.132	-	[kWh]	-	1.056	-
Energy [kWh]	Usable Energy at Beginning of Life (Battery System)	38.0		-	0.119	-	[kWh]	-	0.950	-
Energy [kWh]	Usable Energy at End of Life (Battery System)	30.4		-	0.095	-	[kWh]	-	0.760	-
Voltage [V]	Nominal Voltage (Battery System)	350-360	as high as possible in the respect of the defined voltage window	4.4	-	4.5	[V]	35	-	36
Voltage [V]	Voltage Range - Full Performance (Battery System)	300 to 400		3.8	-	5.0	[V]	30	-	40
Voltage [V]	Voltage Range - Reduced Performance (Battery System)	260-400	to be fixed on the basis of the selected solution capability	3.3	-	5.0	[V]	26	-	40
Voltage [V]	Nominal and Voltage Range (Modular Pack)	<60	Maximum module voltage not higher than 60 Vdc to be compliant with voltage class A limits (maintenance, service and easy disassembly for second life and/or recycling)	-	-	n/a	[V]	-	-	60

A-Segment BEV - VEHICLE (Full pack)			
Power [kW]	Peak Discharge Power (2 s) - BoL	120	nice to have (optional)
Power [kW]	Peak Discharge Power (10 s) - BoL	100	10 s power required at 40% SoC at temps between 25° and 50°C
Power [kW]	Continuous Discharge - BoL	70	1 min to maintain the max speed in EV Mode (hyp. Starting from 95%SOC to 15%SOC)
Power [kW]	Peak Charge Power (2 s) - BoL	150	2 s regenerative charge acceptance power possibly required at upper defined % SOC at temps between 25°C and 50°C.
Power [kW]	Peak Charge Power (10 s) - BoL	120	10 s regenerative charge acceptance power possibly required at upper defined % SOC at temps between 25°C and 50°C.
Power [kW]	Continuous Charge - BoL	100	Continuous charge acceptance power at temps between 25°C and 50°C.
Power [kW]	Peak Discharge Power and Duration (2s) - EoL	96	nice to have (optional)
Power [kW]	Peak Discharge Power and Duration (10s) - EoL	80	nice to have (optional)
Power [kW]	Continuous Discharge - EoL	56	nice to have (optional)
Power [kW]	Peak Charge Power and Duration (2s) - EoL	120	nice to have (optional)

Cell			Unit	Module		
-	-	0.38	[kW]	-	3	
-	-	0.31	[kW]	-	2.5	
-	-	0.22	[kW]	-	1.75	
-	-	0.47	[kW]	-	3.75	
-	-	0.38	[kW]	-	3	
-	0.313	-	[kW]	-	2.5	
-	-	0.30	[kW]	-	2.4	
-	-	0.25	[kW]	-	2	
-	0.175		[kW]	-	1.4	
-	0.375		[kW]	-	3	

A-Segment BEV - VEHICLE (Full pack)				Cell			Unit	Module		
Power [kW]	Peak Charge Power and Duration (10s) - EoL	96	nice to have (optional)	-	0.300		[kW]	-	2.4	
Power [kW]	Continuous Charge - EoL	80	nice to have (optional)		0.250		[kW]	-	2	
Power [kW]	Continuous Charge - Plug-in Charging	22	22kW (@380V / 32A) Delivered from On-Board Charger, DC Input to Battery, 30°C	-	0.069		[kW]	-	0.55	
Power [kW]	Continuous Charge - Fast Charge - SoC range and time	100	for 1500 s		0.313		[kW]		2.5	
Current [A]		350	Maximum current that system will see for 10 s, limited by wiring and fusing.			87.5	[A]			87.
Current [A]	Max. Current in Charge (10 s pulse)	400	Maximum current that system will see for 10 s limited by wiring and fusing.			100	[A]			10
Application Performance	Duty cycles	WLTC Class 3								
Application Performance	Usage Pattern		As external temperatures profile we will apply a Turin-like climate mean values. The number of duty cycles as well as the down time periods per daily routine will be representatives of typical vehicle usage							
Application Performance	Estimated Pack RMS Power [kW]	8	Average between NEDC and WLTC		0.025		[kW]		0.2	

A-Segment BEV - VEHICLE (Full pack)			
Life Expectation	Expected No. of Cycles / Range	1,000 cycles / 90% SoC 38 MWh	Charge Depleting mode (ICE off)
Life Expectation	Range before EoL (SoC window)	5% - 95%	
Life Expectation	Calendar Life	15 years	Ok @ 30 °C, 100% SoC and 80% of initial capacity
Life Expectation	Energy Throughput before EoL [MWh]	38	
Round trip efficiency	Energy Efficiency [%]	95%	
THERMAL			
Operating Conditions	Typical Operating Temperature - Discharge (min, max)	-25 to 55 °C	
Operating Conditions	Typical Operating Temperature - Charge (min, max)	0 to 45 °C	
Operating Conditions	Extreme Operating Temperatures (min, max)	-30 to 60 °C	Extreme conditions are not relevant (optional)
Storage Conditions	Storage Temperature (min, max)	-20 to 55 °C	values updated for demonstrator
Storage Conditions	Max Allowable Self Discharge (Wh/month)	≤100 Wh / month	

Cell			Unit	Module		
5		95	[%]	5		95
	15		[years]		15	
141			[kWh]	1125		
	95		[%]		95	
-	-	0.31	[Wh/ month]	-	-	2.5

Urban Truck - VEHICLE (Full pack)				Cell			Unit	Module	
Subtopic	**Specifications / Requirements**	**Desired Values**	**Note**	**Min**	**Nom**	**Max**		**Min**	**Nom**
Energy [kWh]	Nominal Energy at Beginning of Life (Battery System)	200-395	BoL energies (installed and usable) to satisfy the desired EoL usable energy considering a CD SoC window of 75-80% (from 100 to 20-25%) for usable energy and a loss of capacity of 20% of useable initial one on the life. Volvo: 3-6 battery pack installed in the vehicle.	0.12	-		[kWh]	1.0	
Energy [kWh]	Usable Energy at Beginning of Life (Battery System)			-	-		[kWh]		
Energy [kWh]	Usable Energy at End of Life (Battery System)			-	-		[kWh]		
Voltage [V]	Nominal Voltage (Battery System)	600	As high as possible in the respect of the defined voltage window	-	4.4	-	[V]		35.3
Voltage [V]	Voltage Range - Full Performance (Battery System)	500-750		3.7		n/a	[V]	29.4	

Urban Truck - VEHICLE (Full pack)			
Voltage [V]	Nominal and Voltage Range (Modular Pack)	**<60V**	Maximum module voltage not higher than 60 Vdc to be compliant with voltage class A limits (maintenance, service and easy disassembly for second life and/or recycling)
Power [kW]	Continuous Discharge - BoL	**100-130**	1 min to maintain the max speed in EV Mode (hyp. Starting from 95%SOC to 15%SOC)
Power [kW]	Continuous Charge - BoL	**22 (AC) / 150 (DC)**	Continuous charge acceptance power at temps between 25°C and 50°C.
Power [kW]	Cold Crank Discharge Power at (-30°C)		values extrapolated (in terms of power) following German Standard LV124 (optional)
Application Performance	Duty cycles	Volvo dynamic cycle	Reference Cycles are NEDC and WLTP Class 3
Life Expectation	Calendar Life	**8-10 years**	Ok @ 30 °C, 100% SoC and 80% of initial usable capacity
Storage Conditions	Storage Temperature (min, max)	**-20 to 55 °C**	values updated for demonstrator

Cell			Unit	Module	
		n/a	[V]		
0.06		0.08	[kW]	0.5	
0.01		0.09	[kW]	0.11	
			[kW]		
8			years	8	
-20		55	°C	-20	