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3BELIEVE

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

Technical specifications and test protocols for the battery

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1	28.09.2020	Michele Gosso & Raffaella Rolli	Initial submission for internal review
2	02.10.2020	Laida Otaegui, Marta Cabello, Marcus Fehse	First internal review
3	06.10.2020	Boschidar Ganev	Pre-submission review; formatting, reference updates.
4	13.10.2020	Omid Rahbari	Additional contribution
5	21.10.2020	Maxime Montaru	Additional contribution on 2nd life tests protocols
6	27.10.2020	Boschidar Ganev	Final review prior to submission

Project Abstract

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

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

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

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

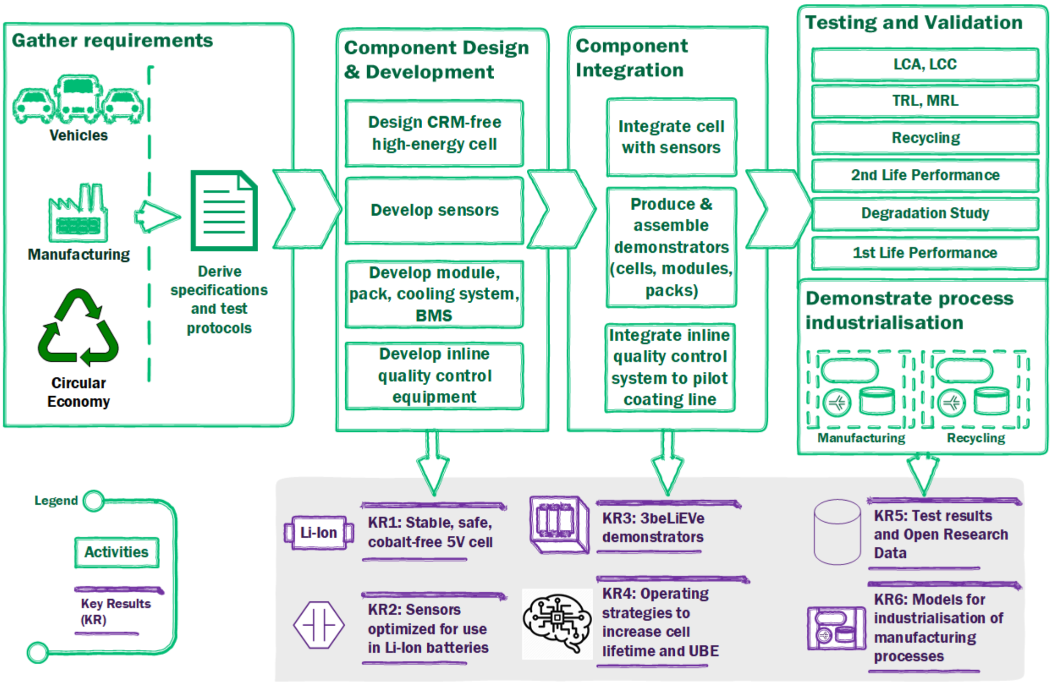

Figure 1: Overview of major 3beLiEVe project steps

Executive Summary

This document describes the technical specifications of the 3beLiEVe battery system on cell, module and pack level to the extent that they are known at time of writing. These early specifications are given in section 2, along with pointers to the documentation where the final specifications will be detailed.

Section 3 lays out the testing plan to be applied to the final demonstrators of 3beLiEVe project at cell, module and pack level, in order to ensure the technical requirements, documented in *D1.1 Consolidated requirements for the 3beLiEVe battery pack*, are met for each considered application (PHEV and BEV cars and EV 16 tonne truck). It should be noted that these are the tests to be applied to the final demonstrators from the project. Testing procedures for component or software development leading up to the final demonstrators are not included in this document. Finally, the number of cells needed to perform the defined tests is estimated and given at the end of section 3. Any needed clarifications on currently unknown specifications or deviations from the plan in final testing will be accordingly documented in the later project deliverables.

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List of figure and tables

List of abbreviations

Acronym / Short Name	Meaning
BEV	Battery Electric Vehicle
BMS	Battery Management System
BOL	Beginning of Life
BP	Battery Pack
C_n	Capacity value of a cell in Ah declared by the cell manufacturer
CC	Constant Current
CD	Charge Depletion
CS	Charge Sustaining
CV	Constant Voltage
DC	Direct Current
DOD	Depth of Discharge
DP	Direct Parallel
EODV	End-of-discharge-voltage
EOL	End of Life
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
HPPC	Hybrid Pulse Power Characterisation
$I_{c,max}$	Maximum continuous charge current specified by the manufacturer
ICA	Incremental Capacity Analysis
$I_{dp,max}$	Maximum discharge pulse current specified by the manufacturer
I_t	Reference test current in amperes (A) which is expressed as $I_t = C_n/1$
KPI	Key Performance Indicator
kWh	Kilowatt-hour
OCV	Open Circuit Voltage
OEM	Original Equipment Manufacturer
OT	Opposite Tabs
PHEV	Plug-in Hybrid Electric Vehicle
qOCV	Quasi-Open Circuit Voltage
RC	Resistor-capacitor
RT	Room Temperature
SOC	State of Charge
SOH	State of Health
SP	Series/Parallel
TBC	To Be Confirmed
$V_{\text{min pack}}$	Minimum allowed voltage for battery pack
WLTC	Worldwide Harmonized Light Vehicles Test Cycle
WLTP	Worldwide harmonized Light Vehicles Test Procedure

1. Introduction

The objective of this deliverable is to document the system specifications, based on the requirements gathered and documented *D1.1 Consolidated requirements for the 3beLiEVe battery pack*. The specifications comprise electrical, mechanical, thermal, production, and cost specifications. These apply to the high-voltage battery, including its subsystems (e.g. battery cells, sensors, BMS, cooling, housing). This is outlined in the following section 2. It should be noted that in most instances, specifications are indicative, as the elaboration of the exact designs and specifications is the subject of the project and will thus become more concrete as the project progresses.

In section 3, this deliverable documents the tests and protocols needed to ensure the requirements are met and to ensure consistent testing and assessment of the final prototypes in WP7. This includes various testing protocols to identify the electrical, thermal, ageing and safety performance on cell level (section0), module level (section 3.3), and pack level (section 3.4).

2. Technical specifications of the high-voltage battery

The technical specifications of the high-voltage battery are derived from the requirements explained in deliverable D1.1. Those technical specifications are related to cell, module, sensors and system level. This section describes the specifications known at time of writing. All specifications will be further elaborated in the course of the project.

2.1. Cell

The cell format selected for the final demonstrators is a pouch cell with opposite-side tabs. The geometrical dimensions are currently fixed at 30.15 x 9.97 x 1.5 cm, though this may change slightly to adjust for conformity with typical automotive formats – this was under discussion at time of writing. The pouch cell format is selected because this allows relatively easy experimentation with sensor integration, and because all production facilities involved in the project can produce this format, providing for consistency in the upscaling process.

The cathode chemistry will feature a LNMO spinel as the active material, which is provided by project partner HALDOR TOPSOE. Three spinel materials were under investigation in WP2 at time of writing. The anode active materials will be graphite and silicon, provided by project partner ELKEM. A high-voltage electrolyte, which is needed to withstand the working voltages of up to 4.8V in the cell, is supplied by project partner ARKEMA (Note: depending on the selected cathode active material, this cycling range might be slightly modified). The final material selections and recipes will be documented in *D2.2 Final material data report and definition of final 3beLiEVe cell chemistry*.

In terms of production quantities, the following is envisaged. Around 10 – 20 pouch cells with a 70Ah capacity will be produced. These will be used to demonstrate the achievement of the volumetric energy density target of 750Wh/L on cell level. A further 200 – 250 cells with a ~30Ah capacity will be produced. These will have the same outer dimensions as the 70Ah cells, but a lesser thickness. These 30Ah cells will be used for integration into the modules and battery packs. At a nominal voltage of 4.4V, the 30Ah cell should have an energy content of 132Wh and the 70Ah cell an energy content of 308Wh. Final cell prototypes are expected to be produced in the first half of 2022 at project partner CUSTOM CELLS ITZEHOE’s facilities. The final cell design and quantities will be documented in *D6.1 FAT report on prototyped cells*.

2.2. Module

Following requirements, the modules will feature a maximum voltage of 60V DC for safe handling and testing. So far, a design decision to connect 8 cells in series inside each module has been taken. Given the cell nominal voltage of 4.4V, this results in a module nominal voltage of 35.2V. This simple series-only configuration was chosen on one hand to avoid any unwanted balancing currents that occur between cells switched in parallel with each other (which can lead to accelerated aging and degradation), and on the other hand to minimize the number of sensors and ancillary system components (e.g. circuit boards). Further work in WP4 will elaborate the geometric design, cooling integration and pressure to be applied to the cells inside the module. The final design of the module will be detailed in deliverable *D6.2 Final design and specifications of module and pack*.

2.3. Sensors, cooling system, BMS

Three different types of sensors are available for inclusion in the battery pack. A nanoplasmonic sensor, to be integrated inside the pouch cell, is provided by project partner INSPLORION. A multi-purpose sensor that is envisaged to be affixed on the outside skin of every cell and featuring temperature, impedance, strain and pressure sensing, is provided by SENSICHIPS. Finally, a module-level sensor to sense temperature and corroborate the measurements of the aforementioned on-cell sensor is provided by NXP. The NXP chip will also facilitate the I2C-bus-based communication of all sensors with the BMS. The communication topology is already partially defined and will be documented in *D4.1 Preliminary BMS design and sensor integration concept*. The design of the individual sensors will be more fully documented in *D4.2 Sensors final design*.

The cooling system is, at time of writing, in early stages of development. The aim is to integrate the cooling fluid ducts into the walls of the module, and to allow actuation of variable flow and pressure, controlled by the BMS. The variable pressure may also be used to vary the pressure on the cells for optimum performance.

foxBMS[1], provided by FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V., is an open-source BMS that will be further developed in 3beLiEVe to receive and process the signals from the above-mentioned sensors, and to manage the whole system from a thermal and electrical perspective using the sensor inputs to unfold an improved operating strategy.

The final specifications of the cooling and BMS will be given in *D4.3 Adaptive cooling systems and final BMS design*. The BMS will also receive an additional software component for an operating strategy using machine learning - to be documented in *D4.4 Advanced diagnostics and adaptive operating strategy using machine learning*.

2.4. Battery pack

On system level, the requirements for PHEV, BEV and EV truck applications have yielded three maximum outer dimensions and weights for the battery packs:

- PHEV (Fiat 500X): 850 x 390 x 190 mm and 95 kg
- BEV (Segment A/B): 1500 x 1100 x 150 mm and 300 kg
- EV (Volvo truck FL 16 tons). 1500-1700 x 700-800 x 200-230 mm.

In this project, two battery packs (systems) each with an energy content of around 12 kWh will be produced. One will be dimensioned for a 100V nominal voltage (cf. Figure 2), while the second one will be implemented

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[1] https://foxbms.org/

in a 200V variant. These voltages are chosen to demonstrate scalability to 400V and 800V applications, respectively. Figure 2 shows a schematic for the electrical layout of the 100V pack. The 200V pack will have two instead of four strings in parallel, with each string having six instead of three modules in series, in order to maintain the same energy content but attain double the voltage.

Furthermore, the designs will seek to ensure easy disassembly and recyclability, in line with the requirements, for instance a reduction or complete avoidance of adhesive pastes used to stabilise cells within the module. The module enclosure will be designed for light weight and sustainability. A focus will be on the reduction of metals and stainless steel.

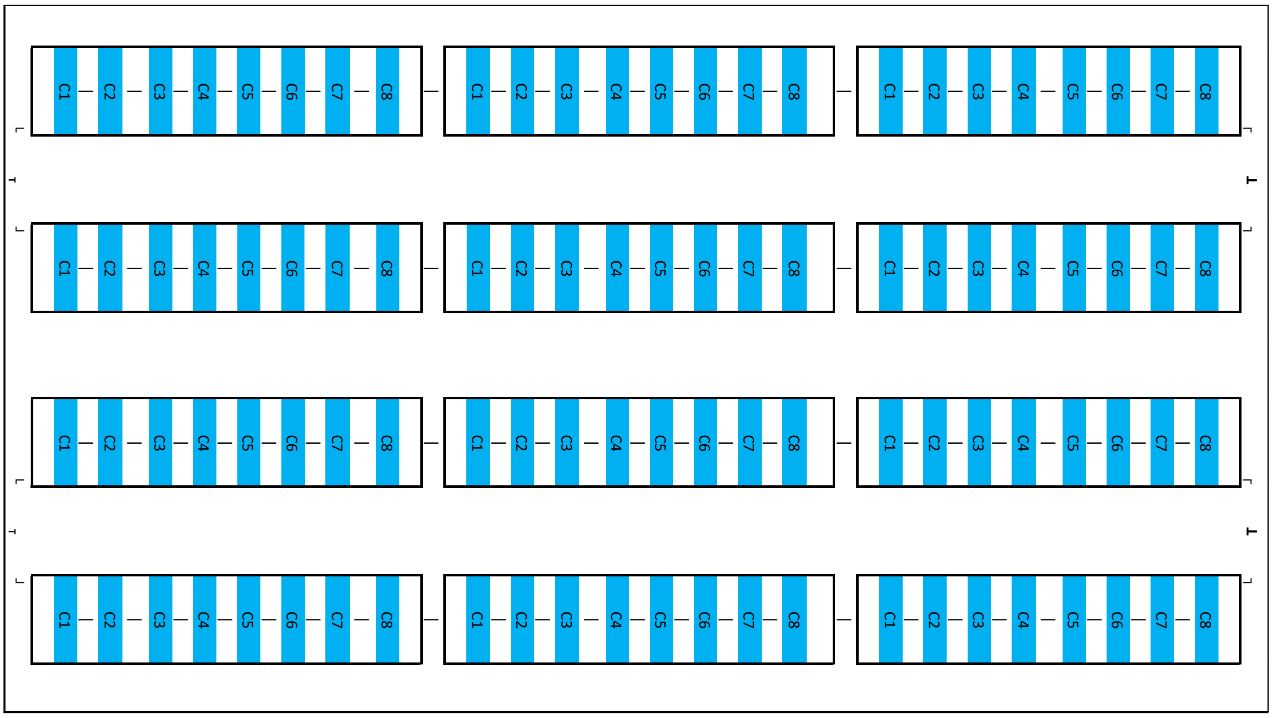

Figure 2: Schematic of the electric topology of the 100V battery pack.

Each small blue rectangle represents a cell. Eight cells in series are encapsulated in one module. Each module contains 8 sensors from INSPLORION, 8 sensors from SENSICHIPS, and one sensor from NXP. The pack total is therefore 96 INSPLORION and SENSICHIPS sensors each, and 12 NXP sensors. An additional current sensor is envisaged for each string of the pack, so in this case four.

Module and pack production and assembly including sensors, cooling system and full integration will be performed by project partner VALEO.

The estimated 2025 production cost on system level amounts to 138€/kWh. Factoring in revenues expected to be achieved from use in a second-life application, as well as revenue from recycling at end of life, a target final lifecycle cost of 90€/kWh is expected to be demonstrated on pack level. This will be evaluated and documented in *D7.4 Ex-post assessment report, including LCA/LCC*.

3. Definition of testing and validation protocols

In the research project 3beLiEVe, next generation lithium-ion battery prototypes are developed and produced. For these new cells, safety aspects as well as achievement of the targeted KPIs must be ensured. This can only be achieved by comprehensive testing of the prototypes. Additionally, to ensure reliable design and operation of battery systems for automotive and industrial applications, system management, including battery management and thermal management, is indispensable. Such system-level supervisors are based on efficient models, which include electro-thermal and lifetime models. For this purpose, battery model development is needed, which includes electrical, thermal and lifetime models. Necessary modeling is performed in WP4.

To address the above points, a set of experiments is performed in 3beLiEVe at cell-, module- and system-level and described in the following chapters.

3.1. Approach to testing procedure definition

A selection among all the existing standards for testing cells, modules and packs has been performed. Nine existing international standards have been selected as a baseline for test procedure definition in 3beLiEVe:

- EN 61427-2:2015, Secondary cells and batteries for renewable energy storage - General requirements and methods of test - Part 2: On-grid applications
- IEC 61427-2:2015, Secondary cells and batteries for renewable energy storage - General requirements and methods of test - Part 2: On-grid applications
- IEC 62660-1:2018, Secondary lithium-ion cells for the propulsion of electric road vehicles
- IEC 62660-2:2018, Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 2: Reliability and abuse testing
- IEC 62660-3:2016, Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 3: Safety requirements
- ISO 12405-4:2018, Electrically propelled road vehicles — Test specification for lithium-ion traction battery packs and systems.
- ISO 16750-3:2012, Road vehicles - Environmental conditions and testing for electrical and electronic equipment – Part 3: Mechanical loads
- SAE J2464_200911, Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing
- SAE J2929_201302, Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-based Rechargeable Cells.

Another reference pillar for testing has been identified in the white paper “Test methods for improved battery cell understanding” [1] .

Finally, the experience of the project partners has been used as a guideline to identify testing cycles, representing the real usage of the battery in the vehicle.

3.2. Testing and validation protocols for cell testing

Battery cell tests can be classified according to their purpose on the one hand (e.g. safety testing, performance testing, ageing testing, check-up testing, electrical and thermal characterisation), but also according to the characteristic values determined with them on the other (e.g. capacity, resistance, OCV). A typical electrical characterisation on cell level includes capacity test, hybrid pulse power characterisation (HPPC) test, and open circuit voltage (OCV) test. As the electrical parameters are temperature-, current-, SOC- and lifetime-dependent, characterisation has to be performed at every state that shall be analysed. The existing standards regarding battery testing (IEC 62660-1 and ISO 12405-4) are summarized in Table 1.

Table 1 – Characterisation tests defined according to the IEC 62660-1 and ISO 12405-4 international standards

Test item	Test type	Condition	IEC 62660-1	ISO 12405-4:2018 (pack/system)
Preconditioning	Cycling	Temperature (°C)	25	25
		Charge	Standard charge	Standard charge
		Discharge	0.2C	2C for high power
				C/3 for high energy battery pack
		cycles	5	5
Energy and capacity	Constant current discharge	Temperature (°C)	−20, 0, 25, 45	−18, 0, 25, 40
		Charge	standard charge #	standard charge §
		Discharge	1C, 10C, 20C, Imax, C/3, 2C and 5C*	1C, 10C, 20C, Imax for high power pack
				C/3, 1C, 2C, Imax for high energy pack
		cycles	2	2
Power and resistance	charge/discharge Pulse test	Temperature (°C)	−20, 0, 25, 45	−18, 0, 25, 40
		Discharge	0.2C, 1C, 5C, 10C, C/3, 2C, Imax*	Imax, dis
		Duration	10 s	0.1 s, 2 s, 10 s, 18 s
		Charge	1/3C, 1C, 5C, 10C 2C, Imax*	0.75*Imax, dis
		Duration	10s	0.1 s, 2 s, 10 s
		SOC	50%	80%, 65%, 50%, 35%, 20%
Energy efficiency	Pulse charge/ discharge	Temperature (°C)	−20, 0, 25, 45	0, 25, 40
		Discharge	1/3C, 1C, 5C, 10C	Time dependent
		Duration	10s	
		Charge	1/3C, 1C, 5C, 10C	Time dependent
		Duration	10 s	
		SOC	50%	65%, 50%, 35%

standard charge procedure and exit conditions as defined by cell manufacturer

§ standard charge procedure and exit conditions as defined by pack manufacturer

* additional current upon request by the customer

3.2.1. Tests on cell level

The different cell tests to be applied are detailed in the following sections:

Preconditioning

Before starting the other testing sequences, the cell is conditioned by performing a certain number of cycles in order to ensure stabilisation of the battery cell. According to IEC 62660-1, which is used for cell characterisation, the preconditioning test consists of 5 times full charge/discharge cycles at room temperature after the cell has been fully charged with a constant current (CC) and constant voltage (CV) with the standard charge procedure defined by the cell manufacturer. The discharge current is 0.2C until the minimum cut-off voltage is reached, followed by 30 min rest. A preconditioning test based on the definitions of IEC 62660-1 is shown in Table 2.

Table 2 – Pre-conditioning tests defined according to the IEC 62660-1 standard

Step	Item	Current	Time	Exit conditions
1	Test setup check (Discharge)	C/5	10s	V<Vmin V>Vmax T>55°C
2	Standard charge	Recommended by the manufacturer	Specified by the manufacturer	V>Vmax Current < C/20
3	Rest		30 min	Time
4	Discharge	C/5	6 hours	V<Vmin
5	Rest		30 min	Time
6	Repeat steps 2-5			

Energy and capacity

The test is used to obtain the cell's capacity and energy content as a function of C-rate and temperature. When several charge rates are used, more information can be obtained, like the (fast charge) efficiency. According to IEC 62660-1, the capacity test consists of two times constant current discharge until the minimum cut-off voltage at room temperature after the cell has been fully charged with the standard CC-CV charge procedure defined by the manufacturer. The chosen discharge currents are C/3, 1C and 2C. Each test is followed by a 1-hour rest. A capacity test based on IEC 62660-1 is shown in Table 3.

Table 3 – Energy and capacity tests defined based on the IEC 62660-1 standard

Step	Item	Current	Time	Exit conditions
1	Test setup check	C/5	10s	V<Vmin V>Vmax T>55°C
2	Standard charge (CC/CV)	Recommended by the manufacturer	Specified by the manufacturer	V>Vmax Current < C/20
3	Rest for thermal stabilisation		1 hour	Time
4	Discharge	C/3	3.5 hours	V<Vmin
5	Rest		1 hour	Time

6	Standard charge (CC/CV)	Recommended by the manufacturer	Specified by the manufacturer	V> Vmax Current < C/20
7	Rest		1 hour	Time
8	Discharge	1C	1.5 hours	V<Vmin
9	Rest		1 hour	Time
6	Standard charge (CC/CV)	Recommended by the manufacturer	Specified by the manufacturer	V>Vmax Current < C/20
7	Rest		1 hour	Time
8	Discharge	2C	1 hour	V<Vmin
9	Rest		1 hour	Time
10	Repeat for other discharge currents			

Power and resistance

The power and resistance test is known in different standards also as Hybrid Pulse Power Characterization (HPPC) test. Its goal is the analysis of the power capability of the investigated battery under different conditions, i.e. charge and discharge, current rate, ambient temperature and state-of-charge (SOC). This test is performed during the initial characterization at the beginning of life (BOL), during the check-up tests when the cells are cycled, and at the end of life (EOL). The test results can be used for equivalent circuit model parameter identification. The obtained pulses are fitted with the governing equation of a first order or second order RC circuit. In this test, the battery cell is excited with constant current pulses with a 10 s duration for charge and discharge currents, following by a 10 min rest time between charge and discharge pulses. The current pulses have been summarized in Table 4. Each charge pulse is followed by a discharge pulse to maintain the SOC constant, with a 10 min rest period in between. After each complete pulse train, 1 h rest is applied for thermal stabilisation. Later the cell is discharged to 5% SOC, which is followed by another 1 h thermal stabilisation period. The complete test profile, considering, for example, a cell with 20 Ah capacity, is given in Table 4 and Figure 3.

The discharges after each full pulse train are based on the actual capacity at C/5, as defined during the detailed capacity tests that precede the HPPC tests.

Table 4 – HPPC tests defined according to the IEC 62660-1 standard for 100% SOC and 95% SOC

Time (s)	Current (A)	Current rate (C)	Time (s)	Current (A)	Current rate (C)	Time (s)	Current (A)	Current rate (C)
0	0	0	11497	0	0	23174	-6.66667	-1/3
1	-20	-1	12097	0	0	23175	0	0
3600	-20	-1	12098	100	5	23775	0	0
3601	0	0	12108	100	5	23776	20	1
7201	0	0	12109	0	0	23786	20	1
7202	4	1/5	12709	0	0	23787	0	0
7212	4	1/5	12710	-100	-5	24387	0	0
7213	0	0	12720	-100	-5	24388	-20	-1
7813	0	0	12721	0	0	24398	-20	-1
7814	-4	-1/5	13321	0	0	24399	0	0
7824	-4	-1/5	13322	200	10	24999	0	0
7825	0	0	13332	200	10	25000	40	2

8425	0	0	13333	0	0	25010	40	2
8426	6.666667	1/3	13933	0	0	25011	0	0
8436	6.666667	1/3	13934	-200	-10	25611	0	0
8437	0	0	13944	-200	-10	25612	-40	-2
9037	0	0	13945	0	0	25622	-40	-2
9038	-6.66667	-1/3	17545	0	0	25623	0	0
9048	-6.66667	-1/3	17546	20	1	26223	0	0
9049	0	0	17726	20	1	26224	100	5
9649	0	0	17727	0	0	26234	100	5
9650	20	1	21327	0	0	26235	0	0
9660	20	1	21328	4	1/5	26835	0	0
9661	0	0	21338	4	1/5	26836	-100	-5
10261	0	0	21339	0	0	26846	-100	-5
10262	-20	-1	21939	0	0	26847	0	0
10272	-20	-1	21940	-4	-1/5	27447	0	0
10273	0	0	21950	-4	-1/5	27448	200	10
10873	0	0	21951	0	0	27458	200	10
10874	40	2	22551	0	0	27459	0	0
10884	40	2	22552	6.666667	1/3	28059	0	0
10885	0	0	22562	6.666667	1/3	28060	-200	-10
11485	0	0	22563	0	0			
11486	-40	-2	23163	0	0			
11496	-40	-2	23164	-6.66667	-1/3			

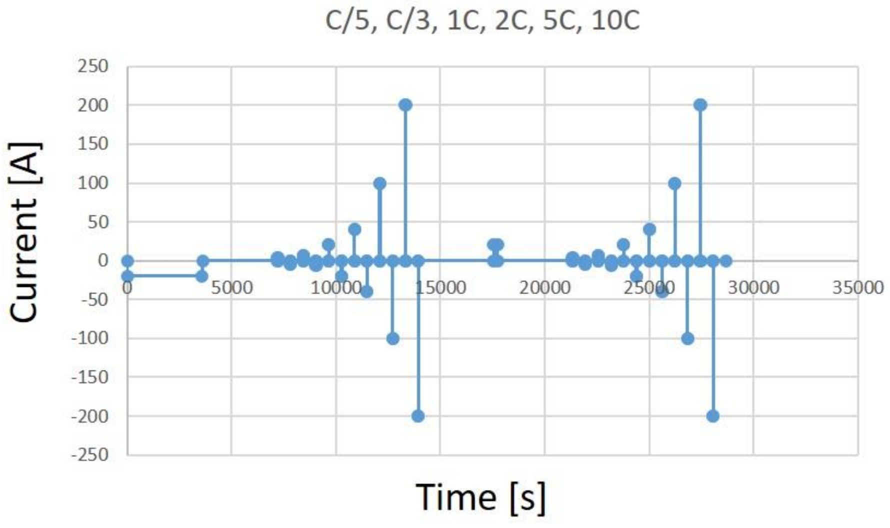

Figure 3: HPPC test current profile.

OCV test

The purpose of this test is to map the relation between the OCV of the cell with the SOC variation. This is achievable by calculating the equilibrium voltage at different SOC levels after 1 hour pause. By referring to the capacity value calculated through the Capacity test it is possible to determine the amount of Ah that need to be discharged or charged to reach these SOC levels. The standard OCV test procedure will take into account 5% steps of the calculated capacity value.

Table 5 – OCV test defined based on the IEC 62660-1 standard

Step	Item	Current	Time	Exit conditions
1	Test setup check	C/5	10 s	V<Vmin V>Vmax T>55 °C
2	Standard charge	Recommended by the manufacturer	Specified by the manufacturer	V>Vmax Current < C/20
3	Rest		1 h	Time
4	Discharge	C/5	30 min	ΔDOD = 5%
5	Rest		1 h	Time
6	Repeat steps 4-5			

qOCV test

In complement to the OCV test, a quasi-OCV (commonly referred as qOCV) test is performed. The idea of this test is to measure the voltage against the SOC under very low current in order to get a voltage response close to the OCV values. The procedure is defined in detail in Table 11.

Calendar life test

The test is intended to determine the ageing and the lifetime of a cell under storage or non-use and is composed of the calendar (storage) life test and regular check-up tests. The chosen test method has been summarized in Table 6.

Table 6 – Calendar life test descriptions

Tests	Conditions
Calendar life test	**Storage**: - Stored under constant temperature (temperature chamber) - Stored under constant voltage (high precision power supply) **Check-up test**: - In order to determine the capacity, power density and regenerative power density of the cell - Performed every 42 days - Performed at the same temperature for all tests

Cycle life test

The test is intended to determine the degradation characteristics of the cell during cycling profile representing laboratory conditions and/or the normal usage condition of BEV/HEV applications. Cycle life tests have been summarized in Table 7.

Table 7 – Cycle life tests descriptions

Standard	Conditions
Laboratory cycle-life test	**Life cycling:** - Constant ambient temperature (temperature chamber) - Constant current discharge - Defined charge regime - Mechanical clamping to create a defined compression, according to the cells installed in modules **Check-up test:** - Performed every 200 full equivalent cycles - Performed at the same temperature for all tests
EV cycle-life test	**Life cycling:** - Constant ambient temperature (temperature chamber) - (Repeated) drive cycle profile discharge - Standard CC-CV charge regime - Mechanical clamping to create a defined compression, according to the cells installed in modules **Check-up test:** - Performed every 200 full equivalent cycles - Performed at the same temperature for all tests

Optimal operation pressure test

Pouch cells with high silicon content in the anode change their volume during operation. Moreover, gassing due to oxidative electrolyte decomposition on cathode and SEI formation on anode are expected, which results in cell swelling. In many applications this volumetric change (swelling) is suppressed by integrating the pouch cells into modules with walls. When swelling, these walls limit the volumetric change of the pouch cells by exerting a counter pressure on the cells. It must be noted that this counterpressure and the extent of swelling of the pouch cells depends on the stiffness of the walls. In other words, the counterpressure is not adjusted to the optimal operating conditions of the pouch cells. This effect is considered in the tests listed in Table 7 by mechanical clamping both for Laboratory and EV cycle test.

As an innovative step in 3beLiEVe, WP4 aims to design a module with adjustable counterpressure. For optimal operation of the cells in the pack, a look-up matrix must be determined to adjust the counter pressure to its optimum as a function of SOH, SOC and probably other quantities, such as the C-Rate and the sign of the electric current, i.e. charging or discharging.

Since no standard test addressing this topic is available yet, such an optimal operation pressure test must be defined in the course of pouch cell development. Current intention is to combine a cell ageing test at 40 °C to maximize ageing speed with an HPPC test to determine the inner electric resistance. For a given point of operation, the counterpressure is varied until the optimal pressure, i.e. the minimum electric resistance in the cell, is found. Over the course of this test, many different operating conditions will be examined in this manner to finally build the look-up matrix to run modules and packs.

Current test parameters are given in Table 12. It must be pointed out that these parameters will need further adjustment and refinement depending on the availability of new pouch cells, its characteristics and technical limitations imposed by the test benches and their communication interfaces.

Safety test (Abuse test)

In order to ensure a safe integration of battery-based electromobility in our society, various international standards and regulation have been introduced for safety testing of lithium ion batteries, which can be used in various abusive environments. Since different hazards, including mechanical, electrical, environmental and chemical, can impose the safe application of lithium ion batteries, a safety analysis is required to ensure the safe integration of lithium ion batteries in real-life applications. The intention of this section is to consider the existing standards for safety test of lithium ion batteries, at cell level for electrical and mechanical abuse conditions, and to define a safety test matrix for cell performance analysis. Table 8 summarises different standards for safety test at cell level.

Table 8 – International standards for safety tests at cell level

Test	SAE J2464	SAE J2929	IEC 62660 -2 (3)
Mechanical	Mechanical shock, penetration and crush/crash test at the cell level are covered	Mechanical shock and vibration test at the cell level are covered	Mechanical shock, crush and vibration at the cell level
Electrical	External short circuit and overcharge/over discharge at cell level	N.A.	External short circuit, Internal short circuit and overcharge/over discharge at cell level
Environmental	Thermal stability and thermal shock and cycling are covered at cell level	Thermal shock is covered at cell level	Thermal stability and thermal shock are covered at cell level
Chemical	Emission and flammability at cell level	N.A.	N.A.

In this section the IEC 62660-2 (3) standard has been referenced for abuse test definition. The nail penetration test has not been defined in IEC 62660-2 (3), therefore the SAE J2464 has been used as reference only for this test.

Test procedures in the mentioned standards are referred to BEV and/or HEV. Cells used for plug-in hybrid electric vehicles (PHEV) can be tested by the procedure for either BEV application or HEV application, according to an agreement between the cell manufacturer and the tester.

Mechanical test- mechanical shock

This test intends to characterise cell responses to mechanical shocks, which may occur in real-life application of vehicles.

For this test, the IEC 62660 -2 refers to ISO 16750-3:2012.

The test is performed as follows:

1- The cell is charged to 100% SOC with a CC-CV charge regime for BEV or to 80% SOC for HEV.
2- In accordance with ISO 16750-3, a mechanical shock detailed in Table 9 is applied to the battery cell. Considering the installation direction of the cells inside the battery pack and the orientation of the mechanical shock imposed to battery pack during accidents, the mechanical shock is applied to the cells in the same direction. Otherwise, the test is performed in all 6 spatial directions.

Table 9 – Mechanical shock test- parameters according to ISO 16750-3

	Description
Pulse shape	Half-sinusoidal
Acceleration	500 m/s2
Duration	6m/s
Number of shocks	10 per test direction

Mechanical test- crush

This test intends to characterise cell responses to external load forces causing deformation, which may occur in real life application of vehicles.

The test is performed as follows:

1- The cell is charged to 100% SOC with a CC-CV charge regime for BEV or to 80% SOC for HEV.
2- The cell is crushed with a round or semi-circular bar or sphere or hemisphere with a 150 mm diameter with a perpendicular force to the larger side of the cells when the cell is placed on an insulated surface. The test continues until one of the following occurs: a) voltage drop equal to one-third of original cell voltage, b) 15% deformation in the cell dimensions occurs, c) force is equal to 1000 times of the cell weight. The test stop criteria is after 24 h or when the temperature decreases by 20% of the maximum temperature. During this test, the cell temperature, and the condition of the cell should be monitored.

Mechanical test- nail penetration (SAEJ2464)

This test intends to characterise cell responses to external penetrating objects into the cell-rupturing separator, which may occur in real life application of vehicles. The test is performed as follows:

1- The cell is charged to 100% SOC with a CC-CV charge regime.
2- A rod with 3mm diameter is used to penetrate the cell perpendicular to a larger side of the cells with 8 cm/s speed. During this test, the cell temperature, and the condition of the cell should be monitored.

Electrical test- external short circuit

This test intends to characterise cell responses to external short circuit which may occur in real life application due to an accident or battery pack opening by an uncertified person. The test is performed as follows:

1- The cell is charged to 100% SOC with a CC-CV charge regime.

2- The cell is short circuited by an external resistance of 5mΩ for 10 min upon agreement between all parties. The recommended sampling steps for voltage and current is 10 ms. The parameters to be recorded during this test are cell voltage, temperature, current, total external resistance . Moreover, the cell condition has to be checked during this phase.

Electrical test- overcharge

This test intends to characterise cell responses to overvoltage, which can happen in real life application of vehicles due to the malfunctioning of BMS unit and charger.

The test is performed as follows:

1- The cell is charged to 100% SOC with a CC-CV charge regime.
2- The cell is then overcharged to above 100% SOC with CC charge regime at room temperature, until the charge procedure cannot be continued due to a failure in cell. Cell voltage, temperature, current, and physical condition must be verified and noted during the test.

Electrical test- forced discharge

This test intends to characterise cell responses to over-discharge which may occur in real life application of vehicles due to the malfunctioning of BMS unit. The test is performed as follows:

1- The cell is discharged to 0% SOC with a CC regime.
2- The cell is then overdischarged below 0% SOC with $1I_t(A)$ for 90 min at room temperature. During this test, the cell voltage, temperature, current, and the physical condition are monitored.

Environmental test- thermal stability

This test scope is to assess the cell behaviour in high temperature environment, which may occur in real life application in vehicles. This condition can be due to the malfunctioning of thermal management system or insufficient cooling in extremely warm environments.

The test is performed as follows:

1- The cell is charged to 100% SOC with a CC-CV charge regime for BEV or to 80% SOC for HEV.
2- The test is performed on a cell stabilised at room temperature in an air convection oven. Then the temperature is raised with 5 K/min rate to 130 °C. The test is terminated after 30 min of storage at the maximum temperature. To prevent cell deformation during this test, cells are clamped analogously to the conditions existing in a battery assembly.

The abuse test results can be described as explained in Table 10:

Table 10 – Test result description

Description	Effect
No effect	No effect, no change in appearance
Deformation	Swelling or deformation in the cell shape
Venting	Liquid electrolyte or mist escapes from the vent
Leakage	Liquid electrolyte escapes from the other parts of the cell except the vent
Smoking	Fume and soot are released from the vent
Rupture	The mechanical opening of the cell casing because of internal or external forces resulting in the exposure of material
Fire	Visible flame from the cell for more than 1s
Explosion	Occurrence in which the cells' components spread rapidly as shrapnel

3.2.2. 3beLiEVe cell test matrix for EV/HEV application

KPI and characterisation tests

The intention of the chosen tests is to characterise the cell performance at different current rates and different temperatures. The tests will be performed on new cells at the beginning of life and also at the end of life for the cells undergoing ageing tests. Since the application of the battery in this project is quite diverse in terms of temperature window and duty level, the approach is to extend the temperature profile and current rates to a range between -20 and +40 °C.

Table 11 – Tests and conditions for the 3beLiEVe characterisation cell test

Test	T °C	C-rate charge	C-rate discharge	SOC%	Description	Number of cells needed
Preconditioning	25 °C	C/5	C/5	0 – 100	5 initial cycles for every tested cell	Every tested cell
Capacity check (discharge) + qOCV	(-20, 0, 25, 40)	Standard Charge @ 25°C; C/20 (qOCV) @ target temperature	C/20 (qOCV), 0.5C, 1.5C, 3.0C		Discharge capacity for different temperatures at different current rates.	2 cells total, consecutive (25 °C, 40 °C, 0 °C, -20 °C)
HPPC test + OCV	(-20, 0, 25, 40)	Standard Charge @ 25°C Pulses according to HPPC test	Pulses according to HPPC test	0 to 100%	every 10% SOC between 10 and 90% SOC @ every temperature; OCV recording in equilibrium before HPPC test and at 0% + 100%	2 cells total, consecutive (25 °C, 40 °C, 0 °C, -20 °C)
Micro pulse test	(-20, 0, 25, 40)	1C, 15 s pulses	1C, 15 s pulses	50%	Continuous charge/discharge pulse until temperature is stabilized. The pulse duration should be as short as possible in order not to change the SOC more than 0.5%	1 cell per temperature

In all tests, the following values are logged at a variable step sampling period. The minimum sample time will be 1 s for the most parts and up to 10 ms for special tests and values (i.e. current and voltage at pulses).

- Cell terminal voltage (V)
- Cell current (A)
- Charged/discharged capacity (Ah)
- Charged/discharged energy (Wh)
- Cell temperature (°C)
- Ambient temperature (°C).

Ageing tests

Table 12 – Tests and conditions for the 3beLiEVe ageing cell test

Test	T °C	C-rate charge	C-rate discharge	SOC%	Description	Number of cells needed
Laboratory cycle life test 1	25	10-20% @ 1C, 20-30% @ 3C, 30-95% @ 1C	1C	10% - 95%	Cyclic aging test with improved operating window (85%) according to KPI Pillar 2	2 cells
Optimal operation pressure test	40	0,5, 1 and 2 C	1	10% - 90% Δ=10%	Determine look-up matrix for optimal pressure	2 cells
Laboratory cycle life test 2	25	Cyc # 1-3: 10-95% @ 1C Cyc # 4: 10-40% @ 3C, 40-95% @ 1C	1C	10% - 95%	Cyclic aging test with improved operating window (85%) according to KPI Pillar 2	2 cells
Laboratory cycle life test ref	25	10-95% @ 1C	1C	10% - 95%	Cyclic aging test with improved operating window (85%) according to KPI Pillar 2	2 cells
EV cycle life test	25, 40		WLTC / VOLVO defined dynamic cycle		100% DOD	2 cells per temperature
Calendar life test	40, 50	1 C (CC-CV)	/	100%, 70%, 30%	Storage for one month at the selected temperature following with chekup test.	2 cells per temperature

Check-up tests

The check-up test is a reduced version of the cell characterisation tests. This check-up is performed at the ambient temperature, after 200 full equivalent cycles for cycling tests, and after one month of storage for calendar tests. Only for calendar tests, a preliminary discharge is performed at beginning of check-up test in order to evaluate charge retention after storage.

The full equivalent cycle is defined as the number of effective cycles at nominal conditions at the beginning of life, which is given by:

$$N_{eq} = \frac{Q_{dis\_actual}}{Q_{dis\_nominal}}$$

where Q_{dis_actual} is the accumulated discharge (Ah) during the cycle life test, $Q_{dis\_nominal}$ is the nominal discharge at nominal current and room temperature at the beginning of life, and N_{eq} is the full equivalent number of cycles.

Table 13 – Check-up Tests and conditions for the 3beLiEVe ageing tests

Test	T °C	C-rate charge	C-rate discharge	SOC%	Description	Number of cells needed
Residual discharge	25°C	-	C/2		Discharge until Vmin after long-time.	For every check-up during calendar tests only
Capacity check (discharge) + qOCV	25 °C	Standard Charge @ 25°C; C/10 (qOCV) @ target temperature	C/10 (qOCV), C/2		Discharge capacity at room temperature and at different current rates.	For every check-up
HPPC test + 2nd capacity check	25 °C	Standard Charge @ 25°C Pulses according to HPPC test	Pulses according to HPPC test C/2 for capacity check	20 to 80	every 30% SOC between 20 and 80% SOC	For every check-up

Abuse tests

The abuse tests as shown in Table 14 will be applied.

Table 14 – Tests and conditions for the 3beLiEVe abuse (safety) test for BEV

Test	T °C	C-rate charge	C-rate discharge	SOC %	Description	Number of cells needed
Mechanical shock	25			100%	For each spatial direction of the cell, 10 shocks pulses with sinusoidal shape is applied as explained in Table 9	2 cells*
Crush test	25			100%	The pressure is applied until the evidences explained in the previous section can be seen	2 cells
Nail penetration	25			100%	The rod is penetrated with 8 cm/s speed and the voltage, temperature and the cell conditions are monitored	2 cells
External short circuit	25			100%	The cell is short circuited for 10 min by an external resistance of 5mΩ	2 cells
Overcharge	25	1C		100%	The cell is charged with constant current until the voltage reaches to 2*V_{max}.	2 cells
Forced discharge	25		1C	0%	The cell is discharged with 1C for 90 min until the test stops because of cell failure	2 cells
Thermal stability	From 25 to 130			100%	The cell is stabilised at room temperature, then the temperature is raised at 5K/min rate to 130°C and remains at this temperature for 30min	2 cells

* if the test result for two cells is not identical, then the third cell will be tested.

3.2.3. Test protocols for 2nd life application

In 3beLiEVe project context, only electrical tests are considered for 2nd life applications. The aim of these tests is to evaluate electrical performance at beginning of 2nd life, i.e. at SOH 80%, until end of 2nd life, i.e. at SOH 50%, and aging performance for 2nd life application. Due to significant difference between usage in EV/HEV application and stationary application, the characterization, performance and aging tests protocols are adapted and are detailed in this section.

Characterization and performance tests

The intention of the chosen tests is to characterize and evaluate cell performances in nominal conditions of 3beLiEVe 2nd life use case (available energy, round-trip efficiency, available power). The tests, which are described in Table 15, will be performed at 25°C and 35°C on cells at the beginning of 2nd life (SOH 80%) and, only at 25°C, each 10% of SOH until the end of 2nd life (SOH 50%) for the cells undergoing aging tests. They will give also additional information for modelling purpose. In complement and if enough cells at SOH 80% are available, the EN 61427-2 standard will be followed in order to evaluate 2nd life opportunity in other on-grid applications. For performance tests, SOC limitations will be set by considering a CC charge until Vmax and discharge until SOC 5% (TBC) of C/3 discharge capacity measured during capacity check.

Ageing tests

The aim of 2nd life cycle tests, described in Table 16, is to evaluate cycling aging behaviour with an average 2nd life profile. These ones consist in the '24h 3beLiEVe 2nd life use case' profile defined in Table 15 for performance test but with reduced rest time in order to perform 2.4 equivalent cycles/day instead of 0.71 equivalent cycles/day in normal use. If enough cells at SOH 80% are available, calendar tests could be performed in order to calibrate calendar contribution in 2nd life model. For cycling test, SOC limitations will be set by considering a CC charge until Vmax and discharge until SOC 5% (TBC) of C/3 discharge capacity measured after full C/5 CC+CV charge (each 25 cycles). The cycling test will be stopped if discharge energy with these SOC limitations is less than 154 Wh[2] for 70 Ah cells and 66 Wh for 30 Ah.

Check-up tests

The check-up test, described in Table 17, is a reduced version of the cell characterisation tests. This check-up is performed at the ambient temperature, after 100 cycles in case of cycling tests, and after one month of storage in case of calendar tests. Only for calendar tests, a preliminary discharge is performed at beginning of check-up test, in order to evaluate charge retention after storage. C-rate values are purely indicative and could be revised before start of the test campaign.

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[2] Considering a BESS of 800 kWh at beginning of second life, it needs 3247 cells of 70Ah - 308Wh at SOH 80% or 7576 cells of 30Ah – 132Wh at SOH 80%. Minimum required energy is 500 kWh at BESS size.

Table 15 – Tests and conditions for the 3beLiEVe 2nd life characterization cell test mode

Test	T °C	C-rate charge	C-rate discharge	SOC%	Description	Number of cells needed
Capacity check	25, 35	CC-CV@ C/3	CC @ C/3	0 to 100%	Charge and discharge capacity/energy in nominal conditions (3 cycles) – 1h rest time after each charge/discharge stage	2 cells per temperature
qOCV	25, 35	CC @ C/20	CC @ C/20	0 to 100%	Low C-rate cycle to evaluate ICA & differential voltage	
OCV, power and internal resistance	25, 35	CC-CV@ C/3	CC @ C/3	0 to 100%	After CC+CV full charge at C/3, complete discharge and charge at same Crate with 1h interruption every 10% SOC between 0 and 100% SOC (ratio of C/3 measured capacity during check-up test)	
Long-time pulses test	25, 35	CC @ C/5, C/3, 0.7C	CC @ C/5, C/3, 0.7C	50%	Charge at C/3 up to SOC 50% (ratio of C/3 measured capacity during check-up test), 1h rest time and, for each Crate, charge 6 min at Crate, 10 min rest time, discharge 6 min at Crate, 10 min rest time	
24h 3beLiEVe 2nd life use case (available energy, round-trip efficiency)	25, 35	CC @ C/5	CC @ C/3	CC charge until Vmax and discharging until SOC TBD% of C/3 discharge capacity measured after full C/5 CC+CV charge	Performance test. Complete charge/discharge until Vmax/Vmin at CC or SOC limit (to be defined). Adjust rest time in order to last 12h for charge period and 12h for discharge period (3 cycles)	
IEC 61427 standard	25, 35			To be defined	On-grid applications performance test	2 cells (optional)

Table 16 – Tests and conditions for the 3beLiEVe 2nd life aging cell test.

Test	T °C	C-rate charge	C-rate discharge	SOC%	Description	Number of cells needed
10h 3beLiEVe 2nd life cycle test	25	CC @ C/5	CC @ C/3	CC charge until Vmax and discharging until SOC TBD% of C/3 discharge capacity measured after full C/5 CC+CV charge (each 25 cycles)	Complete charge/discharge until Vmax/Vmin at CC or SOC limit (to be defined) with 1h rest time or 15 min rest time and Tcell<RT+2°C. Perform check-up test each 100 cycles	2 cells
2nd life calendar test	40, 50		CC @ C/3	100%, 30%	Storage for one month at the selected temperature following with check-up test. Storage SOC is attained by discharging ratio of C/3 measured capacity during check-up test.	2 cells per condition (optional)

Table 17 – Check-up tests and conditions for the 3beLiEVe 2nd life aging tests

Test	T °C	C-rate charge	C-rate discharge	SOC%	Description
Residual discharge	25°C	-	CC @ C/3		Discharge until Vmin after long-time storage – 1h rest time after each discharge stage For each check-up during calendar tests only
Capacity check	25	CC-CV @ C/3	CC @ C/3	0 to 100%	Charge and discharge capacity/energy in nominal conditions (3 cycles) – 1h rest time after each charge/discharge stage
qOCV	25	CC-CV @ C/10	CC @ C/10	0 to 100%	Low C-rate cycle to evaluate ICA & differential voltage
OCV, power and internal resistance	25	CC-CV @ C/3	CC @ C/3	0 to 100%	After full CC-CV charge at C/3, complete discharge and charge at same Crate with 1h interruption every 10% SOC between 0 and 100% SOC (ratio of measured capacity during check-up test)

Long-time pulses test	25	CC @ C/5, C/3, 0.7C	CC @ C/5, C/3, 0.7C	50%	Charge at C/3 up to SOC 50% (ratio of C/3 measured capacity during check-up test), 1h rest time and, for each Crate, charge 6 min at Crate, 10 min rest time, discharge 6 min at Crate, 10 min rest time
Capacity check	25	CC-CV @ C/3	CC @ C/3	0 to 100%	Discharge and charge capacity/energy in nominal conditions (2 cycles) – 1h rest time after each charge/discharge stage

In all tests, the following values are logged at a variable step sampling period:

- Cell terminal voltage (V)
- Cell current (A)
- Charged/discharged capacity (Ah)
- Charged/discharged energy (Wh)
- Cell temperature (°C)
- Ambient temperature (°C).

The default time and voltage sample will be 30s – 10mV. This one will be differentiated in two cases:

- 100ms – 10mV for ‘OCV, power and internal resistance’ and ‘Long-time pulses’ tests in order to monitor dynamical behaviour and
- 30s – 100mV for cycling tests.

Overall cell requirement for 2nd life testing

In total, 20 cells are needed if all the listed tests are performed, with the following repartition:

- 2 for 3beLiEVe 2nd life characterization test
- 2 for IEC 61427 standard (optional)
- 2 for 2nd life cycling test
- 8 for 2nd life calendar test (optional)
- 2 for post-mortem analysis at beginning of 2nd life
- 4 spare cells.

Optional tests could be performed, depending on accelerated 1st life ageing tests possibilities at CEA and in partners’ facilities.

3.3. Testing and validation protocols for module testing

3.3.1. Electrical tests

The electrical characterisation at module level in 3beLiEVe consists of adapted tests based on the tests defined on cell level and includes:

- Module preconditioning,
- Energy and Capacity tests at different temperatures and discharge rates,
- Pulse Power characterization at different SOC levels,
- Drive Cycle tests at different temperatures for BMS algorithm validation.

The tests will be performed with the BMS running and connected to the battery tester and inside a temperature chamber. In addition, the internal liquid cooling system of the battery modules is actively operated by the cooling system of the test bench.

Table 18 – Tests and conditions for the 3beLiEVe module testing

Test	T °C	C-rate charge	C-rate discharge	SOC%	Description	Number of cells needed
Preconditioning	25	1C	1C	0 – 100	5 initial cycles for every tested cell	Every tested module
Capacity check (discharge)	-10, 25	Standard Charge @ 25°C;	C/2, 1.5C, 3.0C		Discharge capacity for different temperatures at different current rates.	1 module
HPPC test	-10, 25	Standard Charge @ 25°C Pulses according to HPPC test	Pulses according to HPPC test	10 to 90	Every 10% SOC between 10 and 90% SOC @ every temperature;	1 module
Drive Cycle test	-10, 25, 40	Standard Charge @ 25°C	WLTC Profile	10 - 95	discharge with a drive cycle profile @ every temperature	1 module

3.3.2. Safety tests

Currently two different concepts on module level are being developed.

The first concept targets to put cooling plates on both sides of each cell to collect the heat at both large cell surfaces. The second concept targets to build a pressurized container around the cells to allow flexible pressure and volume regulation in the module by means of the cooling fluid. It is yet to be determined, which one of these concepts – or maybe even both of them – will be turned into hardware.

Thus, safety tests cannot yet be detailed, but they should cover the following topics:

- Pressure test for cooling plates/pressurized modules
- Leakage test for cooling plates/pressurized modules and cells
- Durability test on pouch cell level, if a conductive fluid, such as water-glycol, is to be used in pressurized modules
- Test of Isolation resistance on module level
- Test of voltage break through level on module level.

Additional tests may need to be added, depending on the final module design(s).

3.4. Testing and validation protocols for pack testing

The electrical characterisation at pack level, according to ISO 12405-4:2018 and internal OEM WLTC/customized cycles, includes:

- Energy and Capacity test at RT and at different temperatures and discharge rates
- Pulse Power characterization at different SOC levels
- Standard Charge for High-power battery pack and system
- Cranking power at low temperature
- Cycle Life
- No-load SOC loss and SOC loss at storage
- Energy efficiency determination
- Energy efficiency at fast charging.

3.4.1. Test sequence

The test sequence for an individual battery pack or system, or a battery pack subsystem shall be based on agreement between the consortium partners.

The tests can be divided in two macro categories:

- General tests
- Performance tests.

Table 19 and Table 20 summarize the general and performance tests at pack level according to ISO 12405-4:2018.

Table 19 – Sequence of general test at pack level

General tests
Pre-conditioning cycles
Standard cycle
Standard discharge
Standard charge

Table 20 – Sequence of performance tests at pack level

Performance tests
Energy and Capacity test at RT
Energy and Capacity test at different temperatures and discharge rates
Power and internal resistance
No load SOC loss
SOC loss at storage
Cranking power at low temperature
Energy efficiency
Energy efficiency at fast charging
Cycle Life

3.4.2. General Tests

Preconditioning cycles

Before starting the real testing sequence, some preconditioning cycles must be done in order to ensure an adequate stabilization of the battery pack for system performance. Table 21 shows most important parameters of preconditioning cycles, according to ISO 12405-4:2018.

Table 21 – Main parameters of preconditioning cycles

	Temperature	C-rate	Number of cycles	Exit conditions	Fulfilled condition
High power battery pack and system	RT (25±2 °C)	2C	5	EODV < $V_{min\ pack}$	$\Delta Cap_{meas}<3\%$ of Cap_{rated}
High energy battery pack and system	RT (25±2 °C)	C/3	3	EODV < $V_{min\ pack}$	$\Delta Cap_{meas}<3\%$ of Cap_{rated}

Standard cycle

The scope of the standard cycle is to ensure the same initial condition for each test of a battery pack or system. A standard cycle has to be performed before each test. It is composed of a standard discharge, a rest period, and a standard charge. Table 22 shows the main parameters of the standard cycle.

Table 22 – Main parameters of standard cycle

	Standard discharge			Standard charge		
	C-rate	**End of phase condition**	**Rest period after phase**	**C-rate**	**End of phase conditions**	**Rest period after phase**
High power battery pack and system	1C	EODV < $V_{min\ pack}$	30 min or a thermal equilibration at RT is reached	Specified by the manufacturer	Specified by the manufacturer	30 min

High energy battery pack and system	C/3	EODV < $V_{min\ pack}$	30 min or a thermal equilibration at RT is reached	C/3 or another specified by the manufacturer	In any case within 8 h	60 min

3.4.3. Performance Tests

Energy and Capacity test at RT

For high-power battery packs and systems, the constant current discharge rates range from 1C to 10C and the maximum permitted C-rate specified by the manufacturer. The discharge has to be terminated at the manufacturer-specified discharge voltage limits depending on discharge rates and temperature.

For high-energy battery packs and systems, the constant current discharge rates range from C/3 to 1C, 2C and the maximum permitted C-rate specified by the manufacturer. The discharge has to be terminated at the manufacturer-specified discharge voltage limits depending on discharge rates and temperature.

The test sequence includes a series of standard discharges (terminated at $V_{min\ pack}$ specified by the supplier) and standard charges performed at RT, according to ISO 12405-4:2018.

Energy and Capacity test at different temperatures and discharge rates

For high-power battery packs and systems, the test has to be performed at three different temperatures (40 °C, 0 °C and −18 °C) with the discharge rates 1C, 10C and the maximum C-rate as permitted by the manufacturer.

For high-energy battery packs and systems, the test must be performed at least at four different temperatures (40 °C, 0 °C, −10 °C and −18 °C) with the discharge rates C/3, 1C, 2C and the maximum C-rate as allowed by the manufacturer.

The test sequence includes a series of standard discharges (terminated at $V_{min\ pack}$ specified by the supplier) and standard charges performed at the different temperatures mentioned above, according to ISO 12405-4:2018.

Power and internal resistance

For a high-power case, the power and internal resistance test determines the discharge pulse power (0.1s, 2s, 10s and 18s) and regenerative (simulating the braking phase) charge pulse power (0.1s, 2s and 10s) capabilities at different SOC and temperatures. The test profile consists of 18s discharge pulse at $I_{dp,max}$ followed by 40s rest period, followed by 10s charge pulse at 75% current rate of the discharge pulse. After the charge pulse, a rest period of 40s follows. The test must be performed at five different temperatures (40 °C, RT, 0 °C, −10 °C and −18 °C) and five percentages of SOC (80%, 65%, 50%, 35%, 20%). Figure 4 shows an example of current profile for high-power application, using a value of $I_{dp,max}$ of 20C. The discharge current is specified as positive and the charge current as negative.

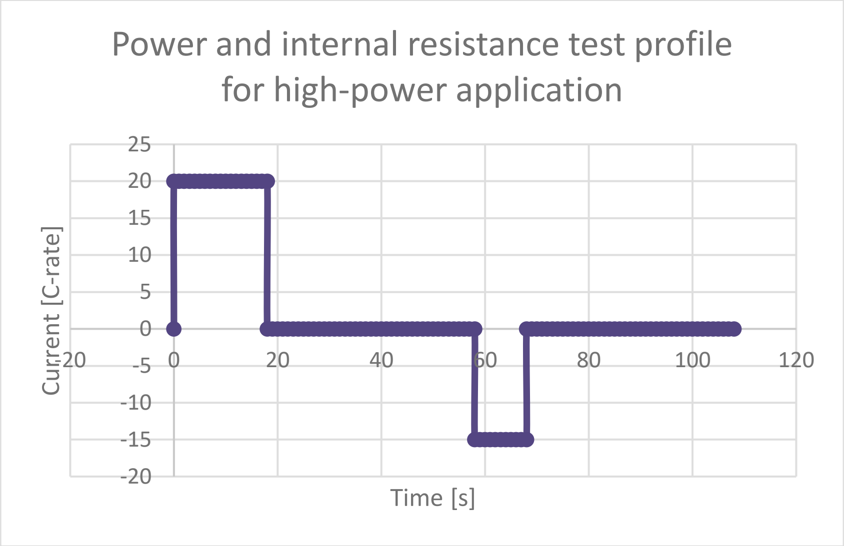

Figure 4: Power and internal resistance test profile for high-power application

For a high-energy case the power and internal resistance test gives the discharge pulse power (0.1s, 2s, 5s, 10s, 18s, 18.1s, 20s, 30s, 60s, 90s and 120s) and regenerative charge pulse power (0.1s, 2s, 10s and 20s) capabilities at different SOC and temperatures. The test profile starts with an $I_{dp,max}$ discharge pulse for 18s followed by a 0,75$I_{dp,max}$ discharge pulse for additional 102s followed by 40s rest period. After the rest period, 20s charge pulse at 75 % current rate of the $I_{dp,max}$ discharge pulse is performed. After the charge pulse, a rest period of 40s follows. The test has to be executed at six different temperatures (40 °C, RT, 0 °C, −10 °C, −18 °C and −25 °C) and five percentages of SOC (90%, 70%, 50%, 35%, 20%).

Figure 5 shows an example of current profile for high-energy application, using a value of $I_{dp,max}$ of 20C. The discharge current is specified as positive and the charge current as negative.

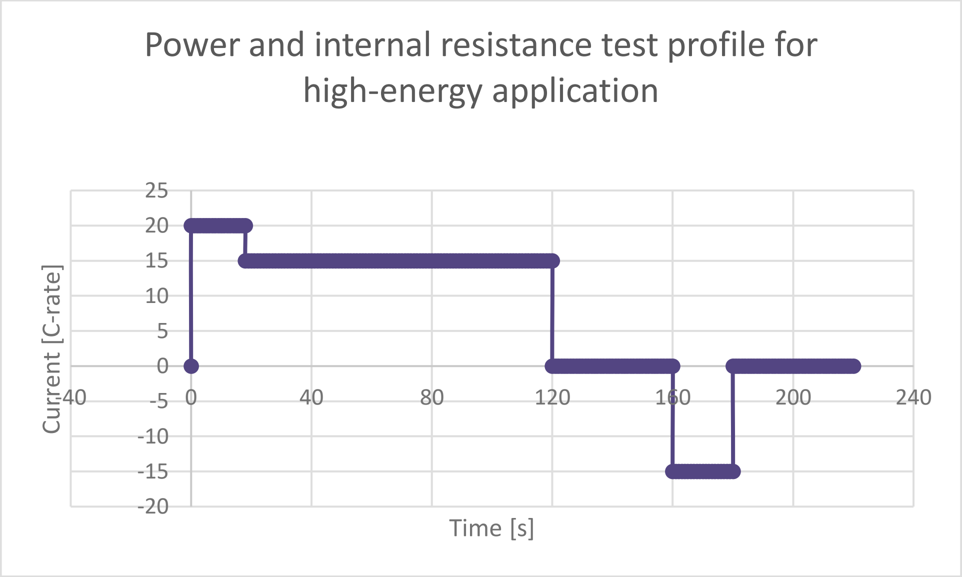

Figure 5: Power and internal resistance test profile for high-energy application

No-load SOC loss

The goal is to measure the SOC loss of a battery system if it is not used for an extended period of time. This test refers to the scenario when a vehicle is in parking mode without charging for a longer time period and therefore the battery system could not be placed on charge.

For a high-power battery system, the no-load SOC loss rate of the battery system has to be measured at two different temperatures and for three different rest periods. The battery system is discharged to 80% SOC and then left at open circuit for a certain time. After the rest period, the remaining SOC shall be determined by a 1C discharge at RT. The considered temperatures are RT and 40 °C, while the rest periods are 24 h (1 day), 168 h (7 days) and 720 h (30 days).

For high-energy battery system the no load SOC loss rate of the battery system shall be measured at two different temperatures and for three different rest periods. The battery system has to be conditioned to 100% SOC by a standard cycle and then left at open circuit for a certain time. After the rest period, the remaining SOC shall be determined by a C/3 discharge at RT. The considered temperatures are RT and 40 °C, while the rest periods are 48 h (2 days), 168 h (7 days) and 720 h (30 days).

SOC loss at storage

The purpose of this test is to measure the SOC loss at storage of a battery system if it is stored for an extended period of time, for example during transportation of the battery system to the testing centre.

The SOC loss at storage of the battery system is measured after a 720 h (30 days) rest period at 45 °C with an initial SOC of 50% or higher, if agreed between manufacturer and user. The remaining SOC after the storage period must be determined by a 1C discharge for high-power battery systems or a C/3 discharge for high-energy battery systems.

Cranking power at low temperature

The cranking power test at low temperatures is performed in order to measure the power capability at low temperatures. The test temperatures could be −18 °C and also −30 °C, depending on the climate zone.

The test for cranking power both at −18 °C and -30°C has to be performed at the lowest SOC level permitted, as specified by the supplier. Table 23 shows the sequence of cold cranking test.

Table 23 – Cold cranking test sequence

Step	Operation	Temperature
1	Thermal equilibration	RT
2	Standard charge	RT
3	Standard cycle	RT
4	Discharge at 1C to 20% SOC or the lowest SOC level allowable as specified by the manufacturer	RT
5	Thermal equilibration	-18°C or -30°C
6	Discharge at constant voltage, setting the lowest permitted system discharge voltage level for 5s	-18°C or -30°C

7	Rest period for 10s	-18°C or -30°C
8	Repeat steps 6 to 7 times	-18°C or -30°C
9	Thermal equilibration	RT
10	Standard charge	RT

Energy efficiency

This test applies to high-power battery systems only. The scope of this test is to determine the battery system round-trip efficiency. The test is performed at three different temperatures: RT, 40 °C, 0 °C, and three different SOC levels: 65%, 50%, and 35%. A rest period of 30 min is inserted before each power pulse sequence. The current profile is described in Table 24.

Table 24 – Energy efficiency current profile

Phase duration [s]	Current [A]
0	0
12	20C or *I*dp,max
40	0
16	−15C or −0,75 *I*dp,max
40	0

The efficiency, expressed as a percentage, is calculated as the ratio of the energy during the discharge pulse divided by the energy of the charge pulse.

Energy efficiency at fast charging

This test applies to high-energy battery systems only. The goal of this test is to calculate the energy efficiency at different fast charging levels.

The test shall be performed with battery systems at RT, 0 °C and *T*min (minimum operative temperature) and three different fast charging levels (1C, 2C and *I*c,max (maximum continuous charge current specified by the manufacturer). After thermal equilibration and conditioning with a standard cycle, the pack must be discharged with a standard discharge followed by a fast charge with a starting current of 1C, 2C and *I*c,max.

Calculation modalities for the energy efficiency at fast charging are reported in detail in Standard ISO 12405-1:2018.

Cycle life

The purpose of this test is to consider the energy throughput effect on battery ageing. It is important to apply a cycle close to the real driving conditions, and to explore the complete usable SOC window using charge-depleting cycles followed by charge-sustaining ones. The tests start at RT. For high power application, SOC normally ranges from 30% to 80%. For high energy application the charge depleting phase SOC swing is from

100% to 20% or other lower limit SOC defined by manufacturer; the charge sustaining phase SOC swing is normally from 25% to 35%. Test sequences for cycle life test are reported in detail in ISO 12405-1:2018.

3.4.4. Customized cycles

Typically, OEMs propose their own cycle life tests dedicated to each application. CRF for the two PHEV and BEV case studies, proposed two cycles, both based on WLTP homologation driving cycle, shown in Figure 6.

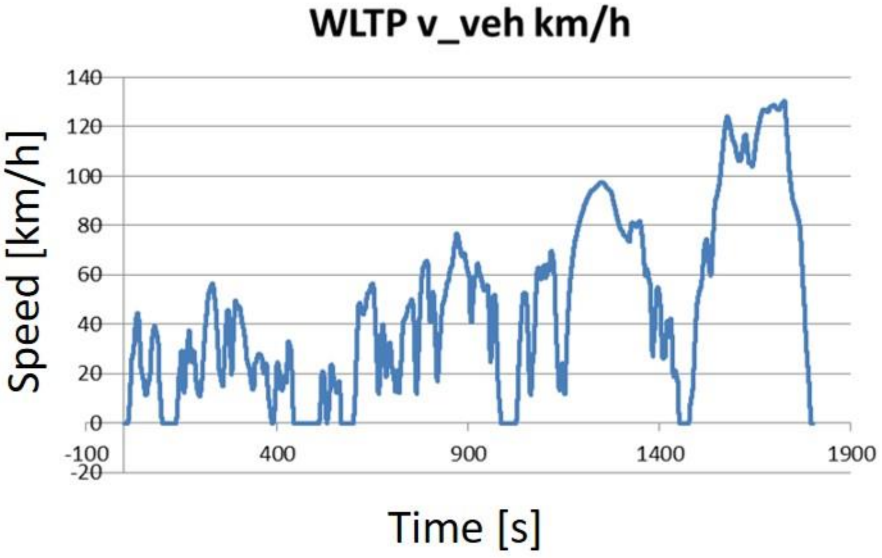

Figure 6: WLTP Class 3 speed profile

For high power – PHEV application, CRF proposed the two power profiles for charge depleting and charge sustaining phases, shown respectively in Figure 7 and Figure 8.

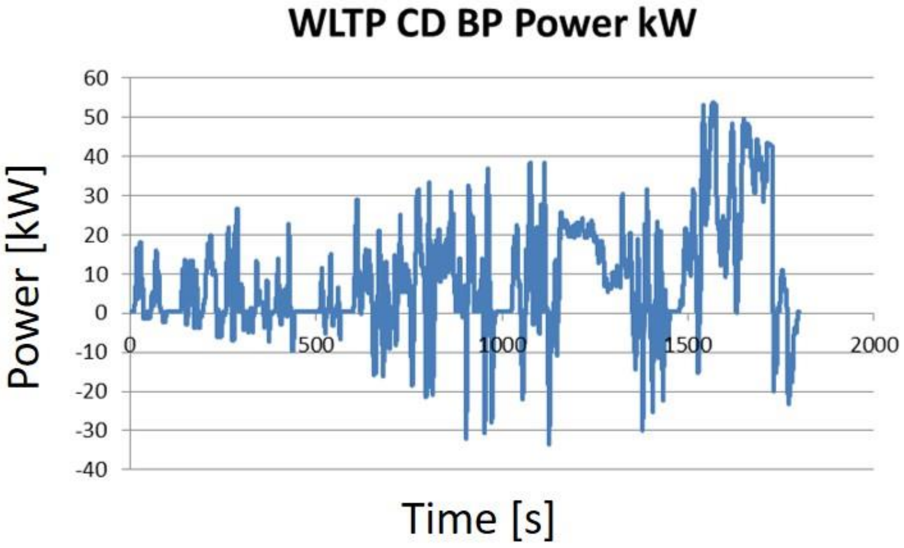

Figure 7: Charge depleting power profile for PHEV application

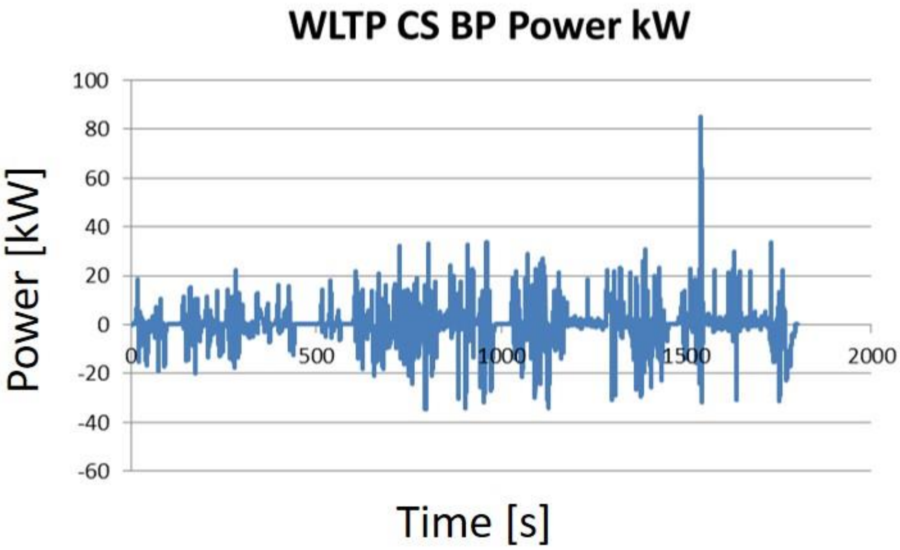

Figure 8: Charge sustaining power profile for PHEV application

For high energy – BEV application, CRF proposed the cycle shown in Figure 9.

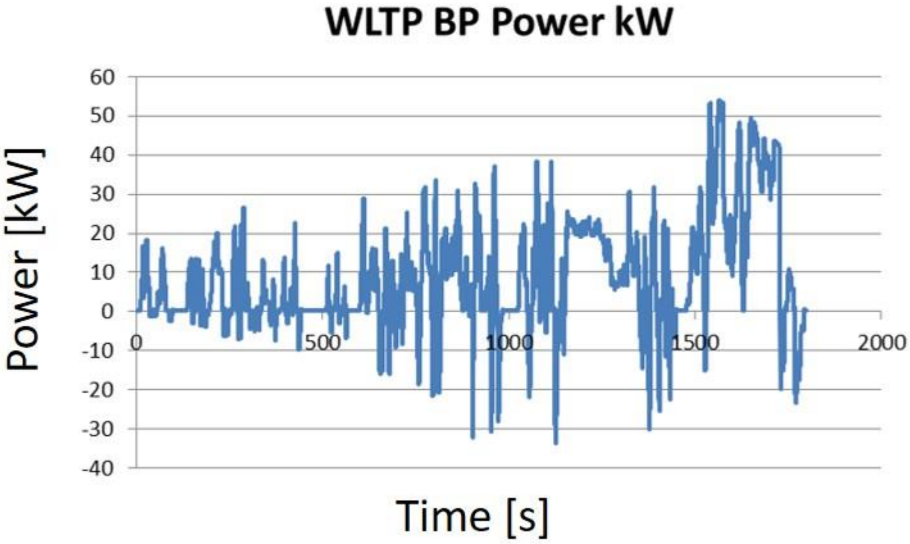

Figure 9: Charge depleting power profile for BEV application

An example of the dynamic cycle for commercial vehicle is shown in Figure 10. This cycle will be the reference point for estimating the lifetime of the pack for a commercial vehicle. Practically, lifetime of the of pack would be estimated from the testing on the cell level using this dynamic cycle with downscaling the current profile according to the cell specification.

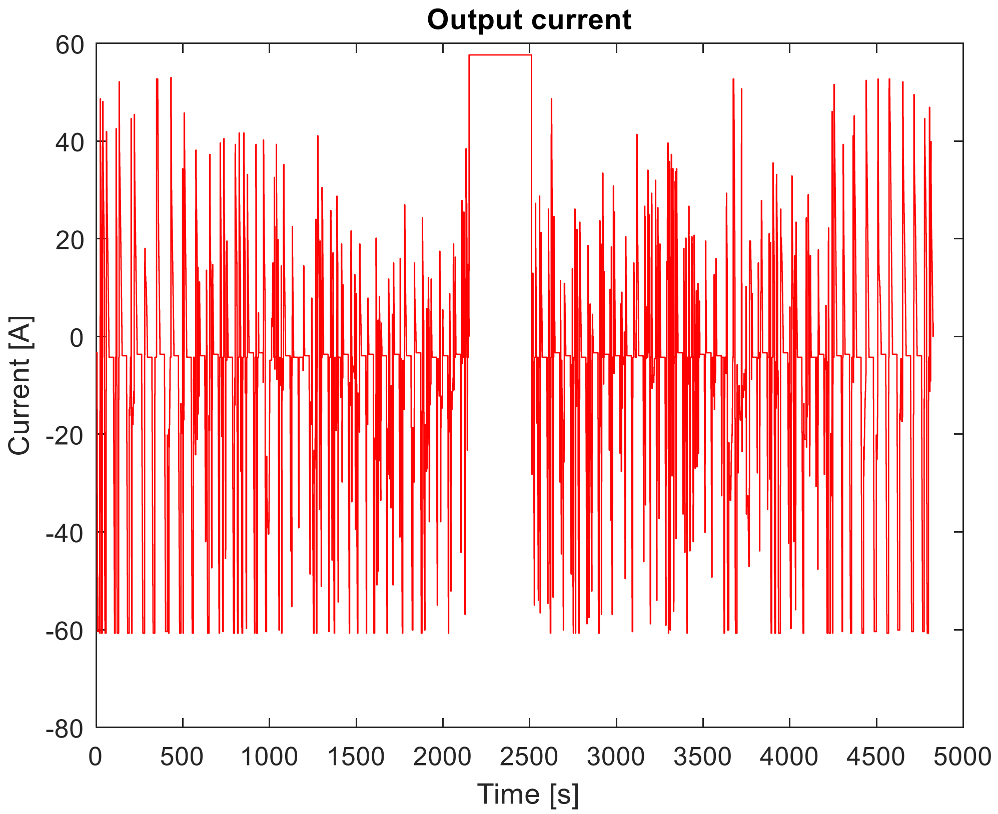

Figure 10: Dynamic cycle for commercial vehicle

3.4.5. Safety tests at pack level

Safety tests at pack level are not forecasted due to the lack of material available to test and due to time constraints.

3.5. Overall need for cells

Basing on previous test definition, the total number of cells needed for testing has been calculated. Table 25 gives an indicative breakdown of the number of cells needed for each test, including spare cells for any needs. The cell requirement is categorized by level and test type:

- Cell tests: characterization, ageing, abuse, 2nd life
- Module tests
- Pack tests.

The module and pack requirements take in account the architecture of module and two demonstrators (1x100V, 1x200V). It should be noted that the number of cells may be adjusted slightly in final testing depending on the exact number of cells finally produced and other considerations that may arise in the project in the meantime, particularly since the computed total is slightly above the originally envisaged number of 250 cells to be produced.

Table 25: Indicative number of cells needed to perform all testing on final demonstrators on cell, module and pack level in WP7.

Category	Test Name	Description	Cells needed	Extra Cells
Characterization	Preconditioning	5 initial cycles for every tested cell	6	3
Characterization	Capacity check + qOCV	Discharge capacity for different temperatures at different current rates		
Characterization	HPPC + OCV	HPPC every 10% SOC between 10 and 90% SOC @ every temperature; OCV recording in equilibrium before HPPC test and at 0% + 100%		
Characterization	Micro pulse test	Continuous charge/discharge pulse until temperature is stabilized. The pulse duration should be as short as possible in order not to change the SOC more than 0.5%		
Ageing tests	Laboratory cycle life test ref	Cyclic aging test with improved operating window (85%) according to KPI Pillar 2; 1C charging	2	2
Ageing tests	Laboratory cycle life test 1	Cyclic aging test with improved operating window (85%) according to KPI Pillar 2; 10% 3C every charge	2	
Ageing tests	Laboratory cycle life test 2	Cyclic aging test with improved operating window (85%) according to KPI Pillar 2; 30% 3C every 3 charges	2	
Ageing tests	Optimal operation pressure test	Determine look-up matrix for optimal pressure	0	0
Ageing tests	EV cycle life test	Dynamic cycle with 100% DOD	8	4
Ageing tests	Calendar life test	Storage at the selected temperature and SOC	12	2
Abuse tests	Mechanical shock	For each spatial direction of the cell, 10 shocks pulses with sinusoidal shape is applied	2	4

Abuse tests	Crush test	The pressure is applied until the evidences explained in the previous section can be seen	2	
Abuse tests	Nail penetration	The rod is penetrated with 8 cm/s speed and the voltage, temperature and the cell conditions are monitored	2	
Abuse tests	External short circuit	The cell is short circuited for 10 min by an external resistance of 5mΩ	2	
Abuse tests	Overcharge	The cell is charged with constant current until the voltage reaches to 2*Vmax.	2	
Abuse tests	Forced discharge	The cell is discharged with 1C for 90 min until the test stops because of the cell failure	2	
Abuse tests	Thermal stability	the temperature is raised at 5K/min rate to 130°C and remains at this temperature for 30min	2	
Module tests	Preconditioning	5 initial cycles for every tested module	32	8
Module tests	Capacity check	Discharge capacity for different temperatures at different current rates		
Module tests	HPPC test	HPPC every 10% SOC between 10 and 90% SOC @ every temperature		
Module tests	Drive cycle test	discharge with a drive cycle profile @ every temperature		
Pack tests	General tests	Preconditioning; Standard cycle; Standard discharge; Standard charge	192	0
Pack tests	Performance tests	Energy and Capacity; Power and Resistance; SOC loss; Cranking power; Efficiency; Cycle life		
		Sum	**270**	**23**
		Total sum	**293**	

4. Conclusions

In this deliverable the requirements resulting from the different domains described in D1.1 were analysed and transformed into specifications. The obtained specifications were described in so far as known in section 2 and also their finalization in the later following deliverables D6.1 and D6.2 was discussed.

Based on the requirements and specifications, detailed test plans were then developed and described at cell level. These include the determination of fixed KPIs of the produced cells, the initial characterization for application on the BMS and tests to determine the electrical and the ageing performance of the cells. A specific section is dedicated to the safety issues and corresponding tests.

Subsequently, based on the defined tests on cell level and the requirements from D1.1, tests on module level were defined and described. These allow the investigation of the relevant parameters under consideration of mechanical bracing, the BMS and the cooling system.

Analogously, the test plan for the pack was developed referring to ISO 12405-4 international standard and to OEMs' tailored cycles.

The requirements, definitions and processes developed in this Deliverable make it possible to check consistently and efficiently whether the KPIs pertaining to cell, module and pack performance are achieved. The specified tests will serve as a basis for work package 7 and the battery tests to be performed therein. By analysing the test results, it will be possible to verify whether the requirements defined in D1.1 are achieved.

5. References

[1] G. M. e. al., „Test methods for improved battery cell understanding - Draft White Paper," 18 4 2018. [Online]. Available: https://www.batterystandards.info/sites/batterystandards.info/files/draft_white_paper_test_methods_for_battery_understanding_v3_0.pdf. [Zugriff am 22 09 2020].

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