CELL-INTEGRATED SENSING FUNCTIONALITIES FOR SMART BATTERY SYSTEMS WITH IMPROVED PERFORMANCE AND SAFETY

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D1.1 REQUIREMENT SPECIFICATION (USE CASES, KPIS AND CELL, MODULE REQUIREMENTS)

LC-BAT-13-2020 - Sensing functionalities for smart battery cell chemistries

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Summary

The requirement specification document lays out the requirements for the cell-integrated sensors (2D temperature and pressure sensors as well as auxiliary electrodes), the read-out electronics, the BMS functions and state estimation algorithms. At first a "virtual" automotive use case based on a Porsche Taycan is defined together with a scaled-down battery system set-up in order to derive requirements for the system components. The battery system setup will be realized in the project and will be used to demonstrate and verify the project results.

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Abbreviations

Symbol / Abbreviation	
ASIC	*Application-specific integrated circuit*
BMS	*Battery management system*
EIS	*Electro-chemical impedance spectroscopy*
EOL	*End of life*
HLS	*High level specification*
IC	*Integrated circuit*
MCU	*Microcontroller unit*
MUX	*Multiplexer*
PC	*Personal computer*
SOC	*State of charge*
SOE	*State of energy*
SOH	*State of health*
SOP	*State of power*
SOS	*State of safety*
TRL	*Technology readiness level*
WLTP	*Worldwide Harmonised Light Vehicles Test Procedure*
VCU	*Vehicle control unit*

1 Introduction

This deliverable is the main outcome of task T1.1. In order to ensure that the research and development work in this project is of industrial relevance a "virtual" automotive use case is assumed based on a real EV. First a short definition and description of a reference vehicle and some high-level requirements set the basis to the derivation of all lower-level requirements in a top-down approach. As this project cannot follow a classical product development approach, a block diagram indicating the scope of this project is presented. This allows to account for the high-level requirements as well as the constraints that arise from the research nature of this project.

As this is a research project with rather low TRL, it is also understood that not all requirements that are derived from an industrial application viewpoint can be met. Nevertheless, these values are given because they are target values and allow for a gap analysis at the end of the project.

This is a living document, since some higher-level requirements may become clearer later in the project, also the resulting lower-level requirements can be derived or updated. Therefore, this document will have to be refined in several rounds.

2 High-Level Specifications (HLS)

In this section first, a target vehicle and application used as a baseline reference are identified. From this starting point, several High-Level Specifications (HLS) can be derived and defined.

2.1 Reference Vehicle and Baseline

As a baseline reference, the Porsche Taycan Turbo S (2019) will be used. The targeted application is a modern EV sports car. This vehicle class and type is chosen, firstly because it shows a demanding application with industry relevance and, secondly, as Porsche was part of the consortium during the proposal preparation and is now going to be part of the project's advisory board, many assumptions in the proposal were already made with this vehicle in mind.

The table below shows the battery system characteristics of the 2019 Porsche Taycan Turbo S. These values are achieved by oversizing the battery with a 11% safety margin (actual vs. used, i.e., the available capacity is capped by the BMS).

Parameter	Value
Battery capacity (actual)	93,4 kWh
Battery capacity (used)	83,7 kWh
Maximum Discharge Power (peak)	560 kW
Maximum Discharge Power (continuous)	460 kW
Maximum Charge Power	270 kW
Maximum Range (WLTP) (OEM value)	416 km

With the advanced sensing technology and the according algorithms developed in SENSIBAT, the goal is to reach the same driving range (416 km under WLTP) over a typical automotive lifetime of more than 8 years and more than 160000 km without the 11% safety margin. A reference driving cycle (e.g. WLTP) and derived power cycle will be defined in D1.2 as part of the test definition.

2.2 Battery System Capacity

The battery system capacity shall be 83,7 kWh.

Rationale: 83,7 kWh is the used battery capacity in the current Porsche Taycan. Using the SENSIBAT technology a safety margin will no longer be necessary to reach the same performance and driving range, without compromising safety.

2.3 Fast Charging

The battery system shall be capable to recharge from 10 % to 80 % SOC in less than 15 min.

Rationale: According to P3 charging index (https://www.p3-group.com/en/p3-charging-index-comparison-of-the-fast-charging-capability-of-various-electric-vehicles-from-a-users-perspective/) the Porsche Taycan fast charging is capable of an average charge power of at least 224 kW over the SOC range from 20% to 80%.

2.4 Cycle Life

The battery system cycle life shall exceed 550 fast charging cycles before reaching 80 % of the battery's initial capacity (end of life - EOL).

Rationale: 550 fast charging cycles represents roughly one fast charging cycle per week over the course of 10 years. The corresponding mileage that can be driven with the recharged power sums up to 160000 km.

3 Block Diagram

In this section the system to be developed would be shown in a block diagram, indicating all the connections and interfaces to other systems and subsystems. For a battery system, this would show how the battery system is part of the vehicle drive train and it would indicate all connections to other vehicle components, such as inverter, charger or vehicle control unit (VCU). In the special case of the SENSIBAT research project, where no full system demonstrator will be developed, the complete battery system block diagram is not of great interest. Instead, a block diagram of the 24 V battery module to be developed in the project and the measurement setup for use with the level-2 sensors are used.

3.1 Level-1 Sensor Measurement Setup (24 V module)

For the SENSIBAT project a battery module demonstrator based on 5 Ah cells with level-1 sensors shall be designed and realized. Figure 1 shows a block diagram of the module demonstrator. The following subsections shortly define the system components depicted as blocks.

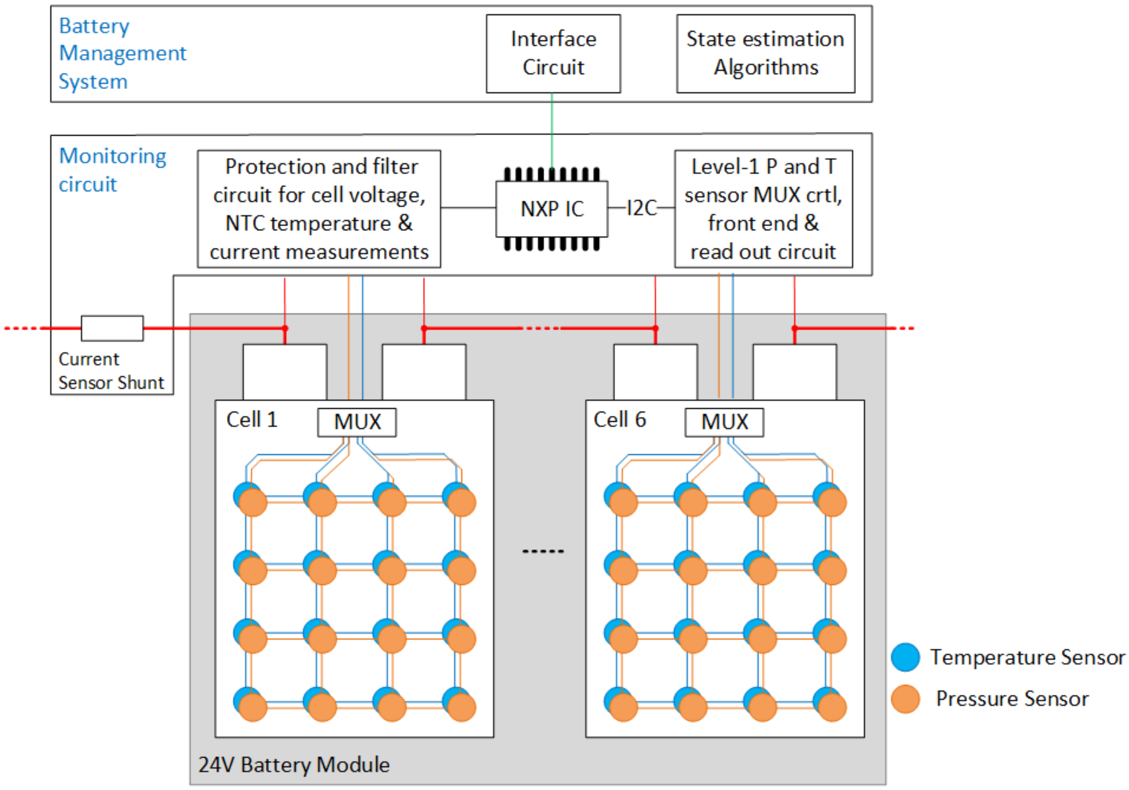

Figure 1: Block diagram of battery module demonstrator

3.1.1 Cell (5 Ah) with level-1 temperature and pressure sensor

For the SENSIBAT project, 5 Ah pouch cells shall be developed that will be equipped with level-1 pressure and temperature sensors. The temperature and pressure sensors shall enable a distributed measurement over the surface of the electrode stack of the cell. A series connection of at least 6 battery cells shall be used to build up a 24 V battery module. The battery module will be connected to an according electrical sink and source (not shown in block diagram) for testing and verification.

3.1.2 Monitoring circuit

The battery module shall be equipped with a battery monitoring circuit. The battery monitoring circuit shall contain a battery monitoring ASIC (application-specific integrated circuit) to measure the cell voltages and cell temperature using a standard NTC sensor as well as the module current using a shunt-based sensor. The monitoring circuit shall enable synchronous voltage and current measurements. Additionally, the battery monitoring circuit shall contain a read-out circuit for the level-1 temperature and pressure sensors. The battery monitoring circuit shall provide a digital data interface to the battery management system (BMS) to transfer the measurement data from the monitoring ASIC as well as the level-1 sensors.

3.1.3 Battery Management System

The battery management system shall provide a digital data interface to the battery monitoring circuit. The battery management system shall run state estimation algorithms using the measurement data from the battery monitoring circuit.

3.2 Level-2 Sensor Measurement Setup (1 Ah Cell)

For the SENSIBAT project a single-cell measurement and verification setup shall be realized for the level-2 sensors. Figure 2 shows a block diagram of the setup. The following subsections shortly define the system components depicted as blocks.

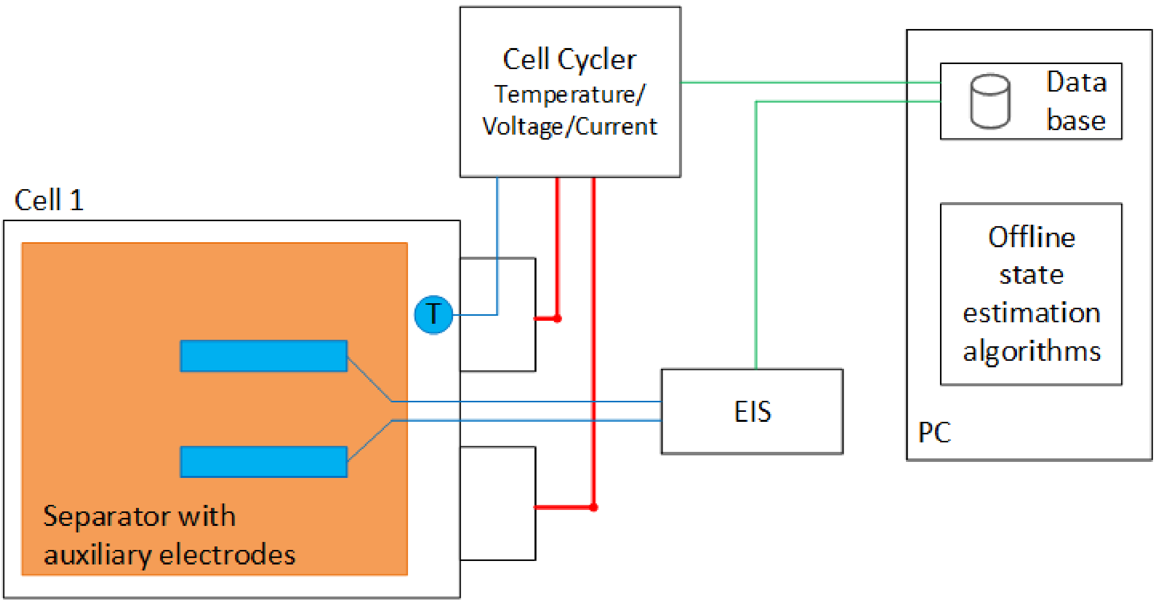

Figure 2: Block diagram of the single-cell measurement setup for cells equipped with level-2 auxiliary electrodes.

3.2.1 Cell (1Ah) with level-2 auxiliary electrodes

For the SENSIBAT project a 1 Ah cell shall be developed that is using a separator with auxiliary electrodes. The auxiliary electrodes shall enable the measurement of the impedance Z of the anode, cathode and separator.

3.2.2 EIS

In order to determine the impedance Z of anode, cathode and separator, electro-chemical impedance spectroscopy (EIS) measurement shall be taken with laboratory-grade equipment. The measurement data shall be automatically transferred to a database.

3.2.3 Cell Cycler

For testing and verification of the sensors and the algorithms based on the EIS data a cell cycler shall be used. The cell cycler shall be able to apply a scaled-down automotive drive cycle to the cell under test. The cell cycler shall be able to measure the cell voltage and current as well as at least one cell temperature from a temperature sensor mounted on the cell surface. The measurement data shall be automatically transferred to a database.

3.2.4 PC

A PC shall be used for data storage and offline battery state estimation based on algorithms using the recorded measurement data.

4 Low-Level Requirements

Using the high-level specification and the system description, low-level requirements are derived in this chapter. For every system component that shall be developed in the SENSIBAT project, a subsection will gather relevant requirements. The requirements should be defined in a way that allows easy definition of the corresponding tests, which is the focus of Task T1.2 and Deliverable D1.2.

4.1 Cell (1 and 5 Ah)

This section describes the requirements for the baseline cell without sensor integration. For additional information some preliminary cell specifications are given first.

The external dimensions of the 5 Ah cell by the partner VMI are expected to be 118 x 158 mm, with R4 corner radius, the active area is expected to be 115 x 155 mm. The cell will incorporate two single-layered and 5-6 double layered negative electrodes (depending on electrode mass loading). The positive electrode will have a size of 110 x 150 mm. It is planned to have 6-7 double-layered positive electrodes in the cell.

For the 1 Ah cells by VMI, it is planned to use negative electrodes with a size of 52 x 72 mm and positive electrodes with a size of 45 x 65 mm. Currently it is planned to have 6-7 double-layered positive electrodes in the cell.

Both cells by VMI (i.e., 1 Ah and 5 Ah) will incorporate graphite based negative electrodes and NMC622 positive electrodes. The organic electrolyte will contain LiPF6 conducting salt and ratio EC:DEC 3:7 (vol:vol) or comparable. The addition of additives like VC in the range of 1-2 % is possible. The pouch bag foil itself consists of a 3-layered compound of polyamide/aluminium/polypropylene. In this compound the polyamide and aluminium ensure the structural integrity of the foils. The aluminium acts as gas diffusion barrier. The polypropylene layer is melted during the welding process to ensure optimal sealing.

The 1Ah cells by ABEE will have external dimensions of 60 x 48 mm. The active areas of positive and negative electrode will be 56 x 43 mm and 58 x 45 mm, respectively. The cell will be use $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ as cathode material, graphite as anode material and a Celgard 2500 separator.

4.1.1 Charge rate

The cell shall enable charge rates of at least 3,2C.

Rationale: This requirement is a consequence of the maximum charging power of 270kW and the battery system size of 83,7 kWh.

4.1.2 Discharge rate (peak)

The cell shall enable peak discharge rates of at least 6,7C.

Rationale: This requirement is a consequence of the peak drive power of 560 kW and the battery system size of 83,7 kWh.

4.1.3 Discharge rate (continuous)

The cell shall enable continuous discharge rate of at least 5,5C.

Rationale: This requirement is a consequence of the continuous drive power of 460 kW and the battery system size of 83,7 kWh.

4.1.4 Operating temperature range

The cell shall have an operating temperature range between -20 °C and 55 °C.

Rationale: Li-ion batteries cannot be used at higher temperatures, so appropriate cooling is needed to avoid cell temperatures higher than the maximum battery temperature. The low temperature limit is a consequence of the use in a vehicle battery system.

4.2 Temperature Sensor (Level 1)

This section describes the level-1 temperature sensor with front-end read-out circuit.

4.2.1 Spatial resolution

The temperature sensor shall enable a spatial resolution of less than 15 mm.

Rationale: Less resolution will hinder detection of local hotspots.

4.2.2 Measurement range

The temperature measurement range shall be from -20 to 60 °C. A measurement range of -20 to 100 °C would be preferred.

Rationale: -20°C is the required minimum operating temperature; 60 °C is the maximum storage temperature for most Li-ion batteries.

4.2.3 Accuracy

The temperature sensing accuracy shall be at least +/-1 °C over the complete measurement range. An accuracy of ± 0.5 °C would be preferred.

Rationale: In order to detect rising temperatures early, accurate temperature sensing is needed. Also, higher accuracy allows operation closer to the maximum cell temperature limits.

4.2.4 Measurement rate

The temperature at every sense point shall be updated with at least 0.2 Hz.

Rationale: Update rate is sufficient to cover slow temperature dynamics inside the cell.

4.2.5 Lifetime

The temperature sensor shall have a lifetime of at least 8 years without degenerated performance.

Rationale: This requirement is a consequence of the battery system life time of more than 8 years.

4.2.6 Withstand temperature

Depending on the sensor integration, the temperature sensor shall be able to withstand temperatures of up to 120-140°C.

Rationale: The drying process before adding the electrolyte to the cells requires temperatures of up to 140°C. Additionally, the sensor feed-through section has to withstand the temperatures during the melting process of the cell sealing.

Additional information for the cell components before construction: The following drying temperatures are applied in high vacuum before the cell is assembled (VMI process):

- Negative electrodes: 120°C
- Positive electrodes: 150°C
- Separator: 60°C
- Pouch foil: 80°C

4.3 Pressure Sensor (Level 1)

This section describes the level-1 pressure sensor with front-end read-out circuit.

4.3.1 Spatial resolution

The pressure sensor shall enable a spatial resolution of less than 15 mm.

Rationale: Less resolution would hinder the detection of local pressure deviations

4.3.2 Measurement range

The pressure measurement shall range from 0 to 1500 kN/m².

Rationale: A typical value for pouch-cell tensioning is 200 to 500 kN/m². With 1500 kN/m² there is enough head space to account for cell aging effects and local peaks.

4.3.3 Accuracy

The pressure measurement shall enable an accuracy of +/-1 % over the measurement range.

Rationale: +/-1 % is sufficient to detect uneven pressure distribution within the cell electrode stack.

4.3.4 Measurement rate

The pressure at every sense point shall be updated with at least 0.2 Hz.

Rationale: Update rate is sufficient to cover slow pressure dynamics inside the cell.

4.3.5 Lifetime

The pressure sensor shall have a lifetime of 8 years without degenerated performance.

Rationale: This requirement is a consequence of the battery system lifetime of more than 8 years.

4.3.6 Withstand temperature

Depending on the sensor integration, the pressure sensor shall be able to withstand temperatures of up to 120-140°C.

Rationale: The drying process before adding the electrolyte requires temperatures of up to 140°C. Additionally, the sensor feed-through section has to withstand the temperatures during the melting process of the cell sealing.

Additional information for the cell components before construction: The following drying temperatures are applied in high vacuum before the cell is assembled (VMI process):

- Negative electrodes: 120°C
- Positive electrodes: 150°C
- Separator: 60°C
- Pouch foil: 80°C

4.4 Monitoring circuit

This section describes the monitoring circuit including the interface to the BMS and excluding the read-out circuit for level-1 temperature and pressure sensors. Besides reading out the level-1 sensors, the monitoring circuit shall provide cell voltage, temperature and module current measurement.

4.4.1 Interfaces to level-1 sensors

The monitoring circuit shall interface to the read-out circuit of the level-1 temperature sensor. The interface shall enable the transmission of all level-1 temperature sensor measurements with an update rate of at least 0.2 Hz.

Rationale: The requirements for the transmission rates is derived from the temperature and pressure sensor update rate.

4.4.2 Voltage measurement rate

The monitoring circuit shall be able to measure all single-cell voltages at a rate of at least 10 Hz.

Rationale: An update rate of 10 Hz (100 ms) can be considered state-of-the-art and is needed to fulfil standard safety requirements in terms of response time.

4.4.3 Voltage measurement range

The monitoring circuit shall provide single-cell voltage measurements with a measurement range from 0 to 5 V.

Rationale: The used NMC I Li-ion chemistry has a typical maximum cell voltage of 4.2 V. A measurement range of 5V leaves enough headspace for internal-impedance-induced overpotential.

4.4.4 Voltage measurement accuracy

The monitoring circuit shall provide single-cell voltage measurements with an error of less than +/- 1 mV.

Rationale: Advanced state estimation algorithms rely on voltage measurements with an accuracy of at least +/- 1 mV.

4.4.5 Temperature measurement rate

The monitoring circuit shall be able to measure a temperature per connected cell as a reference value to the level-1 temperature sensors with a rate of 1 Hz.

Rationale: An update rate of 1 Hz can be considered state-of-the-art and needed to fulfil standard safety requirements in terms of reaction time.

4.4.6 Temperature measurement range

The monitoring circuit shall provide temperature measurements with a measurement range from -20 to 60 °C.

Rationale: -20 °C is the required minimum operating temperature; 60 °C is the maximum storage temperature for most Li-ion batteries.

4.4.7 Temperature measurement accuracy

The monitoring circuit shall provide the possibility to read out temperature measurements with an accuracy of at least +/-1 °C.

Rationale: As a refence this measurement has to be at least as accurate as the level-1 sensor measurement.

4.4.8 Current measurement rate

The measurement range shall be 10 Hz, according to the voltage measurement.

Rationale: The monitoring circuit shall be able to measure the module current synchronously with the cell voltages.

4.4.9 Current measurement range

The monitoring circuit shall provide module current measurements with a measurement range from at least +/- 35 A.

Rationale: The maximum discharge charge rate in the base line vehicle is 6.7C, 35A is 7C for the 5Ah cell.

4.4.10 Current measurement accuracy

The monitoring circuit shall provide a current measurement with an error of less than +/-0,5 %.

Rationale: As the current measurement is integrated to gain e.g., information on the SOC, a high accuracy is required to minimize integration errors.

4.4.11 Interface to BMS

The monitoring circuit shall provide an isolated data interface to the BMS. The data rate has to be sufficient to transmit all measurement data of the level-1 pressure and temperature sensors connected to the monitoring circuit, as well as the cell-voltage, external temperature and current measurement data.

4.5 BMS (Hardware)

This section covers the BMS hardware including the interface to the monitoring circuit. Additionally, the BMS shall provide an interface where raw data and processed data (i.e. minimum and maximum values as well as estimated states) can be read for evaluation (this interface is not mentioned in the block diagram).

4.5.1 Interfaces

The BMS shall provide an interface to the monitoring circuit. The interface is defined by the monitoring circuit.

4.5.2 Computational performance

The BMS shall provide sufficient embedded calculation performance to execute the state estimation algorithms in real time.

4.6 State estimation algorithms (embedded)

This section defines the state estimation algorithms based on level-1 sensors and running embedded on the BMS. The estimation algorithms will be based on equivalent-circuit type models and shall, in general, provide better accuracy and/or additional insights compared to the state-of-the-art cell-level state algorithms, due to 2D measurements of the internal temperature and pressure of the cell. As a reference for all SOC estimation algorithms including the baseline, a laboratory-grade current sensor and current integration will be applied. As a baseline industrial SOC method, a well-known Kalman-filter-based estimator using a production-grade current sensor will be used (with a similar accuracy as the current sensor to be used in the demonstrator module). For all SOH, SOE and SOP algorithms, offline characterization of the cell will be used to find how capacity has degraded and impedance has increased. This will be compared to the output of the corresponding state estimation algorithms.

4.6.1 SOC (state of charge)

The SOC is defined as the ratio of the remaining electric charge to the nominal capacity of the battery.

In many existing SOC estimation algorithms, temperature is not or only coarsely considered. With the input from level-1 sensors, which gives access to the cell internal temperature, and synchronous voltage and current measurement enabled by the monitoring circuit, improved SOC estimation algorithms will be compared to the baseline and the reference SOC, especially investigating how accuracies develop over time.

The SOC algorithm obtained with level-1 pressure and temperature sensors shall provide 2D information on the SOC, identifying for instance heterogeneous lithiation of the electrodes. This involves taking spatial variation of the SOC in the used model in the algorithm into account.

Rationale: Quantification of 2D heterogeneous SOC shall reveal for instance that there are still accessible spots in the anode for further charging. This shall improve high-level requirements, increasing for instance the range of the vehicle.

4.6.2 SOH (state of health)

The SOH is an indicator of degradation of the battery compared to a new battery. SOH is variously defined but the most accepted parameters to derive an SOH value are battery capacity-fade and internal resistance increase. Here, SOH will be defined as the ratio of the actual capacity of the battery to the initial capacity, i.e. the capacity of the battery when it was new. Both capacity values shall be specified at a certain standard discharge condition (e.g. a C/5 constant-current discharge at 25 degrees → see deliverable D1.2). As such, this definition takes both capacity-fade and internal resistance increase into account.

As a baseline to assess the SOH estimation improvements achieved with level-1 sensor-based algorithms, a known method will be used, e.g. based on relating SoC differences to actual charge differences. As for SoC, using more sensor data will be applied to investigate improvements.

The SOH algorithm obtained with level-1 pressure and temperature sensors shall provide 2D information on the ageing of the cell, identifying local ageing spots throughout the electrodes (local SEI growth, local plating, etc.). The used model shall take spatial variations into account to enable this.

Rationale: Quantification of 2D heterogeneous SOH shall reveal for instance that battery degradation is only happening in some local spots, while most of the cell is still healthy. This shall improve high-level requirements, increasing for instance the lifetime of the battery pack.

4.6.3 SOE (state of energy)

The SOE relates to the capacity-fade aspect of SOH. It is a measure of how much energy the battery can deliver under defined conditions. In a vehicle application the SOE can be used to calculate the achievable range with a known driving profile. A similar baseline estimation algorithm can be used as for SOH. Level-1 sensors can be applied to improve these algorithms, e.g. applying data on changed stress in the electrodes related to intercalation, and more precise inclusion of temperature data.

Rationale: The SOE (together with the SOP below) enable improved range estimation in EV applications.

4.6.4 SOP (state of power)

SOP relates to the aspect of internal resistance increase of SOH and provides information about what peak power can be drawn from (or charged to) the battery over a short period. It can e.g. be derived from the baseline

Kalman-filter-based SOC estimation that estimates states and model parameters. Especially the synchronized voltage and current measurements can be applied here to come to an appropriate SOP estimation.

Level-1 pressure and temperature sensors shall provide a 2D representation of the cell impedance, deriving on a 2D polarization voltage representation throughout the cell. Therefore, associated SOP algorithms shall consider this 2D impedance information to compute available power estimates. Again, the spatial variation of impedance needs to be accounted for in the used model.

Rationale: Higher power values could be permitted by the BMS, considering that the internal local voltages through the electrode are more permissive compared with the cell-level voltage limits. This shall improve high-level requirements, allowing for more power to flow through the battery in both charge (increase fast charging) and discharge (increase EV acceleration).

4.6.5 SOS (state of safety)

The SOS is an indicator of how safe the battery operation is, according to the measured variables and estimated states. A safe state is understood as a battery operation which avoid or minimise the occurrence of hazardous internal reaction (e.g. Lithium plating during fast charging, copper-plating due to over-discharge, etc). The SOS estimator shall provide indications to ensure the battery operating variables remains within defined safe windows. As SOS concepts presented in the literature are still in an early maturity stage, this definition shall also be refined throughout the project.

The developed SOS estimator shall provide estimates based on the measurements of Level-1 sensors (voltage, current, temperature and pressure) as well as the information provided by of the remaining state estimates (SOC, SOH, SOE, SOP).

Rationale: This shall improve high-level requirements, increasing battery-pack safety.

4.7 Auxiliary electrode (Level-2)

This section covers auxiliary electrodes to be processed on the separator in the cell electrode stack.

4.7.1 Life time

The auxiliary electrode shall have a lifetime of 8 years without degenerated performance.

4.7.2 Additional requirements

The auxiliary electrodes shall not impact the regular cell capacity and impedance. They shall also not increase aging by preventing any possible reactions between electrode material and battery-internal agents and solvents.

4.7.3 Withstand temperature

Depending on the sensor integration, the auxiliary electrodes shall be able to withstand temperatures of up to 120-140°C.

Rationale: The drying process before adding the electrolyte requires temperatures of up to 140°C. Additionally, the sensor feed-through section has to withstand the temperatures during the melting process of the cell sealing.

Additional information for the cell components before construction: The following drying temperatures are applied in high vacuum before the cell is assembled:

- negative electrodes: 120°C
- positive electrodes: 150°C
- separator: 60°C
- Pouch foil: 80°C

4.8 State estimation algorithms (offline)

This section defines the state estimation algorithms based on level-2 sensors and running offline on e.g. a PC. These estimation algorithms will involve electrochemical, physics-based models to make optimal use of the level-2 sensor measurements. In general, they shall provide better accuracy and/or additional insights compared to the state-of-the-art cell-level state algorithms, due to separated characterisation of the anode and cathode reactions.
As for the level-1 sensors, the SOC reference will be based on a laboratory-grade current sensor and current integration, while a standard Kalman-filter-based SOC algorithm will serve as baseline. SOH/SOE algorithms will have as baseline a method relating differences in SOC to differences in charge, whereas SOP can be linked to the baseline SOC estimation method where state and parameter estimation takes place. Performance of SOH, SOE, SOP algorithms can be found from regular characterization of the cell to assess the actual loss in capacity and increase in impedance.

4.8.1 SOC (state of charge)

The use of level-2 sensors can potentially improve the SOC estimation performance by enabling a more accurate estimate of the parameters of the model used for SOC estimation. This is because the accuracy of the SOC estimate, especially when using an observer or estimator, ultimately comes down to the accuracy of the applied model.

Rationale: Detailed information on the impedance development over time of various parts of the battery gives more detailed information on the battery health (SOH below), which in turn influences the SOC, since even the simplest models used in SOC estimation take some battery impedance into account. The question here is how level-2 sensor information can improve the quality of the model. This depends on which model is used, i.e., electrochemical or ECM (as also used for the level-1 sensors). This shall improve the high-level requirements, increasing for instance the range of the vehicle.

4.8.2 SOH (state of health)

Compared to using level-1 sensors, the additional information of the level-2 auxiliary sensors will be used, for example by fitting physics-based models on the additional measurement data to investigate the evolvement of parameters over time.

The SOH algorithm obtained with level-2 sensors shall provide separated information on the impedance evolution of the positive and negative electrodes. As for level-1 sensors, this requires adding spatial variation to the models. For the level-2 sensors, this involves using physics-based models to be able to attribute the measured impedances to physical phenomena.

Rationale: Separated quantification of the ageing within positive and negative electrode shall provide additional insights on the battery health, allowing for instance to evaluate the level of severity and decide to further extend the use of aged battery packs. This shall improve high-level requirements, increasing for instance the lifetime of the battery pack.

4.8.3 SOE (state of energy)

Similar to the potential improvement of SOC estimation performance by using level-2 sensors, level-2 sensors could also lead to a performance increase by enabling a more accurate estimate of the model used for SOE estimation. Since the SOE is a measure on how much energy is available to the application under defined conditions, which implies during flow of a certain defined current, the development of the battery impedance over time will influence the SOE estimation as well.

Rationale: SOE models will take battery impedance into account in some form. Therefore, more detailed information on the impedance coming from the level-2 sensors improves the model accuracy (model can be physics-based or ECM, similar to SOC estimation), thereby increasing SOE estimation accuracy. This shall improve the high-level requirements, increasing for instance the range of the vehicle.

4.8.4 SOP (state of power)

Similar to SOH, the use of additional level-2 sensor data will be considered, for example by relating measured values to the parameters of a physics-based model. Since SOP relates to battery impedance, the read-out of level-2 sensors is expected to have most impact here.

Level-2 sensors shall provide a separated impedance characterisation for positive and negative electrodes. Therefore, associated SOP algorithm shall consider this electrode-level information to compute more accurate available power estimates.

Rationale: Monitoring electrode-level impedance, higher power values could be permitted by the BMS, considering for instance that the negative electrode polarization voltage is more permissive compared with the cell-level voltage limits. This shall improve high-level requirements, e.g. allowing for more power to flow through the battery in charge (increase fast charging).

5 Risks

Risk No.	What is the risk	Probability of risk occurrence[1]	Effect of risk[2]	Solutions to overcome the risk
1	*There is a risk that some of the requirements defined in this document cannot be met to the full extent due to the research nature of the project.*	*Medium*	*Low*	*A gap analysis can be used to evaluate the reached results and to identify where improvement and further research may be needed beyond the scope of this project.*
2	Knowledge and new research results may have an impact on the requirements defined in this document.	Medium	Low	This document is intended to be a living document, changes due to new research results can be updated in this document and have to be distributed to the project partners.

[1] Probability risk will occur: 1 = high, 2 = medium, 3 = Low

[2] Effect when risk occurs: 1 = high, 2 = medium, 3 = Low

6 Acknowledgement

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Project partners

#	PARTICIPANT SHORT NAME	PARTNER ORGANISATION NAME	COUNTRY
1	IKE	IKERLAN S. COOP.	Spain
2	BDM	BEDIMENSIONAL SPA	Italy
3	POL	POLITECNICO DI TORINO	Italy
4	FHG	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	Germany
5	FM	FLANDERS MAKE VZW	Belgium
6	TUE	TECHNISCHE UNIVERSITEIT EINDHOVEN	The Netherlands
7	NXP NL	NXP SEMICONDUCTORS NETHERLANDS BV	The Netherlands
8	NXP FR	NXP SEMICONDUCTORS FRANCE SAS	France
9	ABEE	AVESTA BATTERY & ENERGY ENGINEERING	Belgium
10	VAR	VARTA MICRO INNOVATION GMBH	Germany
11	AIT	AIT AUSTRIAN INSTITUTE OF TECHNOLOGY GMBH	Austria
12	UNR	UNIRESEARCH BV	The Netherlands

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