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

GA 957273

D5.2 – COST BENEFIT ASSESSMENT

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

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Summary

The main objective of this deliverable is to assess the cost of the cells produced in the SENSIBAT project and to understand if the addition of sensors could potentially lead to an increase of the expected rewards based on the benefits provided by the SENSIBAT sensors. The analysis was based on a bottom-up approach, where the bill of materials was used as a starting point to estimate cost of 1 Ah and 5 Ah with and without sensors. After determining the cost of the cells at pilot-scale level, the costs were extrapolated to industrial-level production.

The findings show that the inclusion of sensors benefit various stages of battery cell production and use. Sensors to measure the potential of the individual electrodes are made with low-cost and scalable printing techniques that have the potential to lower the €/kWh/cycle cell cost. In contrast, pressure and temperature sensors use more complicated deposition techniques which makes them prohibitively expensive for use in each and every cell in the way they are manufactured today. Nevertheless, they use finds place in the development stage where they can be used for early identification of temperature and pressure anomalies that could result in catastrophic failures down the line. Therefore, they offer the promise of shortening battery development cycles and faster market deployment. which could ultimately lower their cost. Ultimately, this report shows the promise of sensor incorporation in battery cells from the economic standpoint.

This deliverable does not include any deviation from the objectives and timings planned in the Grant Agreement of the project.

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Abbreviations

Symbol / Abbreviation	
BL	*Baseline*
BMS	*Battery management system*
CAD	*Computer aided design*
CAPEX	*Capital expenses*
CNC	*Computer numerical control*
DoD	*Depth of discharge*
EU	*European Union*
LFP	*Lithium iron phosphate*
NaCMC	*Sodium carboxymethyl cellulose –* $[C_6H_7O_2(OH)_x(OCH_2COONa)_y]_n$
NMC622	*Lithium nickel manganese cobal oxide –* $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$
NMP	*N-Methyl-2-pyrrolidone –* C_5H_9NO
PVDF	*Polyvinylidene fluoride –* $CH_2{=}CF_2$
rpm	*Rounds per minute*
SBR	*Styrene-butadiene rubber –* $C_{12}H_{14}$
SoH	*State of health*

1 Introduction

The deliverable D5.2 ''Cost benefit assessment'' presents the outcomes of the T5.2 activities in the 5th work package of the SENSIBAT project, ''Testing, validation and assessment (performance, cost, disassembly and recycling)''.

The primary objective of this task is to evaluate the economic implications of manufacturing battery cells equipped with various sensors. This assessment is of paramount importance as the integration of sensors into cells inevitably introduces additional production costs, which need to be justified by the enhanced sensing functionality. These sensors are anticipated to play a critical role in enhancing the safety and performance of the cells throughout their operational lifespan. Hence, it is imperative to gain a comprehensive understanding of the economic impact associated with the inclusion of these sensors.

In this analysis, we utilize the details of the developed baseline cells (D3.3), sensors (D2.2, D3.1), and their integration (D3.4, D3.5) as the foundational inputs. This approach allows for a precise estimation of the associated costs. Subsequently, we delve into a discussion on the benefits brought forth by these sensors within the broader context of the SENSIBAT project. Ultimately, the analysis shows that the inclusion of SENSIBAT sensors presents clear benefits for the battery cell production and use.

2 Perspective

With the shift towards renewable energy sources and the ongoing electrification of the transport, global battery production is projected to rise to over 6 TWh by 2030 (Figure 1). [1] To facilitate this transition and push Europe to the forefront of the global battery industry, several companies have announced battery production plans, reaching a total of 960 GWh of capacity by 2030 in Europe alone. [2]

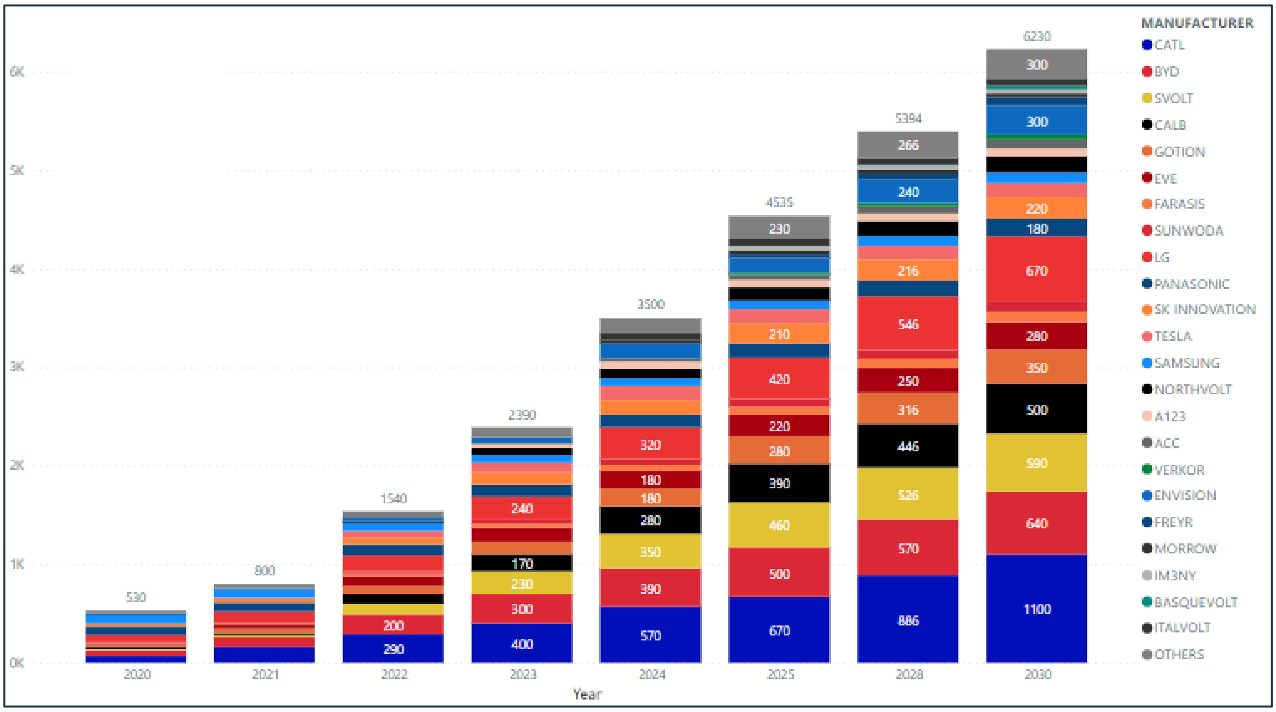

Figure 1. Battery production capacity measured in GWh. [1]

This increase in battery production capacity is critical, but whether it is enough for upcoming challenges is still a matter of debate. Taking into consideration the supply of raw materials and their limited nature, it is imperative to extract as much value from the produced batteries as possible, therefore the battery's service life should also be increased. Doing so requires understanding and timely prevention of the battery degradation mechanisms.

Knowing that battery degradations are accompanied by temperature, pressure, and/or voltage variations, these can be used as proxies to determine the state of the cells and limit safety hazards (e.g., gas evolution, mechanical strain, thermal runaway, unwanted chemical reactions, etc.). In light of this, introducing sensors into cells for real-time sensing of the parameters mentioned above is a promising way to i) monitor the state of individual cells, ii) prevent safety hazards, and ultimately, iii) improve battery performance. With this information, protocols can be designed for optimal cell performance due to a more accurate determination of the safety limits for each cell. Moreover, the sensors provide a more accurate feedback loop that can streamline, speed up, and lower the battery cell development cost. The latter is critical since battery manufacturing is a capital-intensive industry (Figure 2).

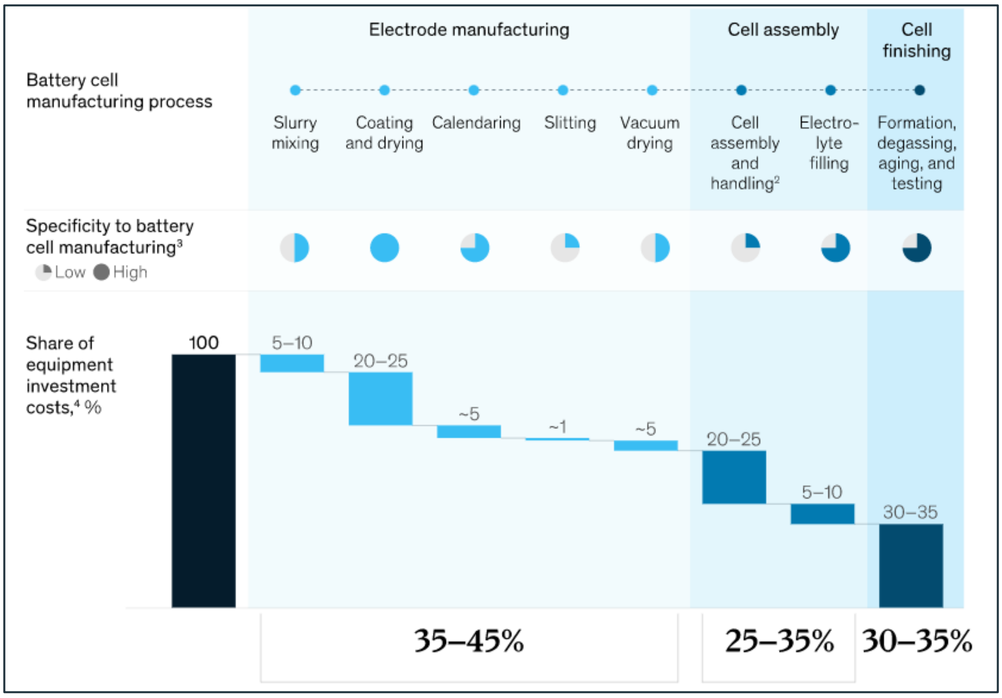

Figure 2. Capital-expenditure of the equipment for a 40 GWh battery-production facility. [2]

Most of the initial equipment cost goes towards coating, drying, assembly, formation, degassing and testing of the cells. [2] Sensors are currently not introduced into the battery cells at an industrial scale as there are no ready-made solutions that can be directly inserted into existing battery production methods. And modifying them would naturally increase the lithium-ion cell production costs, which is undesirable considering the industry's effort to lower the costs of batteries. Therefore, sensors have to be designed in a way to seamlessly incorporate into the existing battery production methods.

2.1 The state of the art in cost analysis

Estimating the cost of battery cell production has several challenges since costs depend on case-by-case industrial activity that is usually confidential. Moreover, the battery cell industry is dynamic and in its infancy, so the production cost is severely affected by continuous know-how improvements. Therefore, there is a large discrepancy in reported costs. For example, the cost assumptions of battery cells range from 84 to 140 €/kWh for state-of-the-art NMC-based batteries. [3] Nevertheless, the majority of the costs of battery cells originate from the materials. In fact, the German Engineering Association (VDMA) estimates that materials cost correspond to 60% of total cell costs, while BMW estimates this number to be 80%. [3]

Traditionally, cost estimation techniques can be divided into three categories: i) analogous; ii) parametric and ii) bottom-up. [4] Analogous techniques apply historical cost data to a new product using regression or neural network models. Parametric approaches use product-specific cost functions that are statistically related to predict costs. The bottom-up approach breaks the product into constituent components and processes and assigns costs for each. The analogous approach is not applicable here, since the product developed in SENSIBAT is sufficiently new that no analogous data exists for similar products. Similarly, the parametric approach is also not suitable since it makes use of databases that contain parameters of technologies alike to the system of interest. Finally, this leaves the bottom-up approach as the most suitable for SENSIBAT.

3 SENSIBAT cost analysis methodology

SENSIBAT is developing an innovative sensing technology capable of real-time measurement of critical internal parameters of Li-ion batteries. By utilizing data generated by these advanced sensors and gaining insights into degradation and failure mechanisms, the project is enhancing the capabilities of the battery management system's (BMS) state estimation functions. The cells produced in SENSIBAT are dubbed as follows:

Table 1. SENSIBAT battery cell nomenclature.

Cell name	Details
BL-1Ah	Baseline 1 Ah cell
BL-5Ah	Baseline 5 Ah cell
L2-1Ah	1 Ah cell with L2 sensor
L1-5Ah	5 Ah cell with L1 sensor

The sensors are designed to be incorporated into existing production methods. While L1 sensors are made with complex microfabrication techniques, L2 sensors are printed on top of Celgard separators. Those dubbed as L1 measure battery cell internal temperature and pressure with spatial resolution, while those dubbed as L2 measure potential, enabling in situ electrochemical impedance spectroscopy (EIS), electrodes' potential and conductivity measurements. The details on the developed sensors are present in D2.2 for L2 and D3.1 for L1, while their integration into battery cells is discussed in D3.3, D3.4 and D3.5.

The aim of SENSIBAT cost analysis is to estimate the costs of producing battery cells with integrated L1 and L2 sensors. The cells in question have capacities of 5 Ah (for L1 sensors) and 1 Ah (for L2 sensors), and are in pouch cell format. To obtain relevant results, a cost analysis is conducted using a bottom-up approach and in several phases, each building upon the previous one:

I. Phase 1: Pilot-scale production
II. Phase 2: Industrial-scale production

In all cases, cost estimation doesn't consider overheads and profits. Therefore, a total cost can be represented with the following equation:

$$C_{total} = C_M + C_L + C_E + C_{EQ} + C_{IN}$$

Where:

C_M is the cost of materials

C_L is the labor cost of the personnel

C_E is the cost of the energy expenditure

C_{EQ} is the equipment cost and maintenance

C_{IN} is the infrastructure cost which includes facility, rent and utilities

4 Phase 1: Pilot-scale production

Material costs for cells are sourced from common material suppliers (e.g. MTI Corp, MSE Supplies, Sigma-Aldrich, etc.). The reported costs are from March 2023. Normalised materials costs for lab-level fabrication of battery cells are presented in Table 1.

Table 2. Normalised materials costs for cells.

Material	Cost	Units
NMC622	0.00045	€/mg
Graphite	0.00032	€/mg
Conductive additive	0.0023	€/mg
Cathode binder	0.0011	€/mg
Anode binder	0.0015	€/mg
Cathode binder solvent	0.00082	€/ml
Anode binder solvent	0.000005	€/ml
Copper current collector	0.0000031	€/mm^2
Aluminium current collector	0.0000027	€/mm^2
Anode tab	0.0015	€/mm^2
Cathode tab	0.0014	€/mm^2
Separator	0.00000063	€/mm^2
Electrolyte	0.98	€/ml
Laminated aluminium pouch foil	0.000068	€/mm^2

The sum of material costs are presented in Table 2 and are provided by FHG and BDM, respectively.

Table 3. Materials costs for sensors.

Sensor	Cost	Units
L1	185.5	€/cell
L2	9.7	€/cell

Considering the information in Tables 1 and 2 within the context of electrode parameters and cell designs, as outlined in D3.2, the overall materials costs for SENSIBAT cells are as follows (Table 3).

Table 4. Materials costs of SENSIBAT cells.

SENSIBAT battery cell	Cost	Units
BL-1Ah	6.5	€/cell
BL-5Ah	24.1	€/cell
L1-5Ah	209.6	€/cell
L2-1Ah	16.2	€/cell

Processing costs herein include all the remaining costs necessary for the fabrication of the cells, including energy expenditure, equipment costs and depreciation and labour costs but excluding the formation step of cells. In order to have a fair comparison, several assumptions were made, as follows:

I. Labor costs were based on average hourly rates for Manufacturing Engineers in Belgium (for 1Ah cells) and Austria (for 5 Ah cells). Sensor costs were obtained from FHG (for L1 sensors) and BDM (for L2 sensors) who are based in Germany and Italy, respectively. This approach is justified by the country of fabrication of respective components and give a more accurate representation of the international battery research effort within the EU.

II. In all cases a 40 h work-week and 260 work-days per year were assumed
III. Semi-industrial pilot line was considered for cell production and assembly with 5 cells produced per hour.
IV. Energy expenditure was averaged at 70 kWh for 1kWh of produced battery. [5, 6]
V. CAPEX were assumed at 1000 €/kWh. [7]

The above brings the processing costs to 15.6 €/cell for 1 Ah and 29.2 €/cell for 5 Ah. The difference originates from different locations of production (i.e., Belgium and Austria, respectively). Processing costs for L1 sensors are 24.1 €/sensor and for L2 are ~0.7 €/sensor.

Considering everything discussed so far, the total cost of the SENSIBAT cells is presented in Table 4.

Table 5. Total costs for SENSIBAT cells.

SENSIBAT battery cell	Cost	Units
BL-1Ah	22.1	€/cell
BL-5Ah	53.24	€/cell
L1-5Ah	286.4	€/cell
L2-1Ah	31.8	€/cell

As can be seen, the type of sensors has a large influence on the final costs of the cells. In fact, just at the materials level only ~10% of the total L2-1Ah materials cost originates from the sensors, while ~90% of the L1-5Ah materials costs are attributed to the L1 sensor (Figure 3). This difference originates from the way the sensors are produced. While L2 sensors consist of graphene/LFP printed on top of the Celgard separator, L1 sensors are made through complex deposition of thin film metals that necessitate the expensive cleanroom environment (as presented in detail in D2.2 and D3.1).

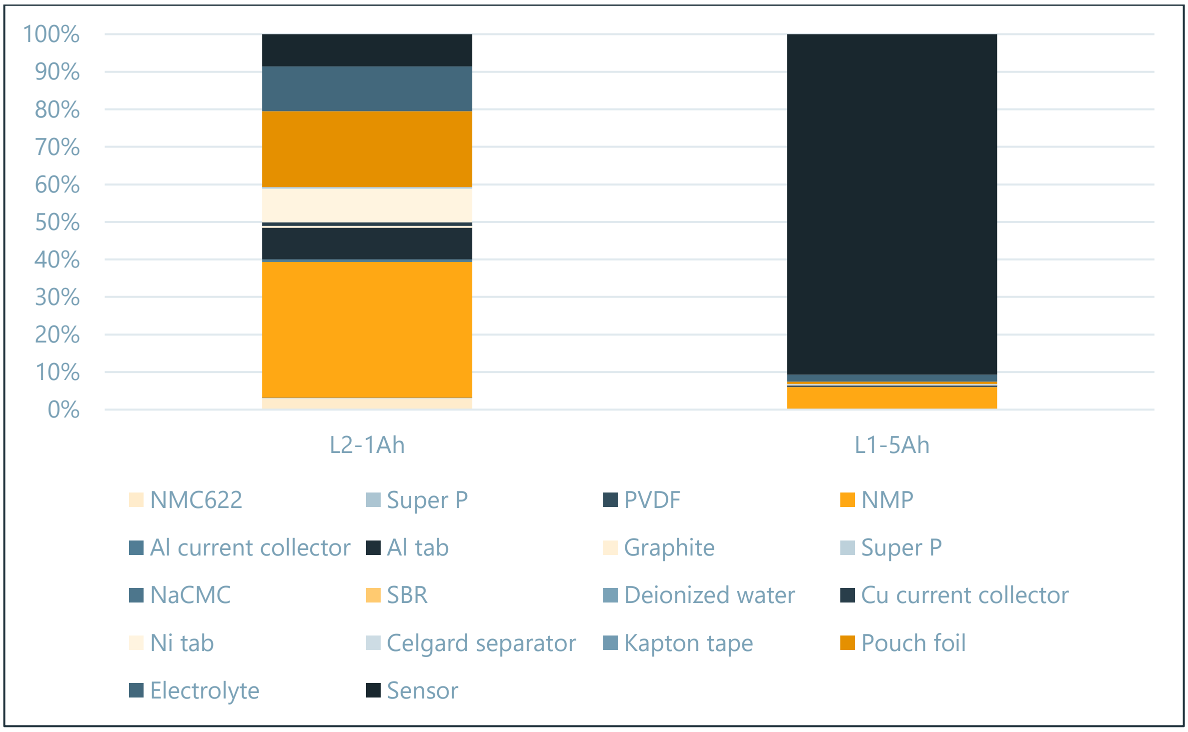

Figure 3. Materials costs distribution for L2-1Ah and L1-5Ah cells.

Moreover, processing costs represent ~70% and ~50% of total costs for L2-1Ah and L1-5Ah cells. It is important, however, to keep in mind that the material quantities used herein are for low-throughput production (i.e. laboratory scale) and the processes are not optimized in terms of efficiency, therefore they do not benefit from economies of scale (cf. Chapter 5 of the present document).

5 Phase 2: Industrial-scale production

Industrial-scale production differs from lab-scale one by the amount of materials input, their yield and the levels of automation. [8] With ton-level, instead of kg-level, of materials, optimized processing and minimized idle time, the costs can be significantly reduced in what is known as economies of scale.

The biggest bottleneck in SENSIBAT cell production is the low number of cells produced per hour. Switching to a fully automated electrode production and assembly line, would allow the production of ~50 cells per hour for 1 Ah and 5 Ah, respectively. [9] This would bring down the 1 Ah and 5 Ah cell costs (without L1 and L2 sensors) to 11.3 €/cell and 43.3 €/cell, respectively. Further switching to an industrial-scale high throughput line, allows for a reduction of the costs down to 6.7 €/cell for 1 Ah and 24.8 €/cell for 5 Ah. [10] Therefore, just by increasing the efficiency of the production line, a cost reduction of ~70% and ~50% can be achieved for 1 Ah and 5 Ah cells.

The next biggest difference between small- and industrial-scale battery production, lies in the cost of raw materials. The cost of a product unit is spread over the number of units, so large quantities naturally command a lower price. Going from 1 kg to 20 kg may yield a price drop of ~40%/kg. [11] Further increase in material amounts to tons, as is needed for GWh-scale production, can lower the price by as much as ~95%/kg. This finally lowers the total price to 0.5 €/cell for 1 Ah and 1.9 €/cell for 5 Ah, a drop of ~97%.

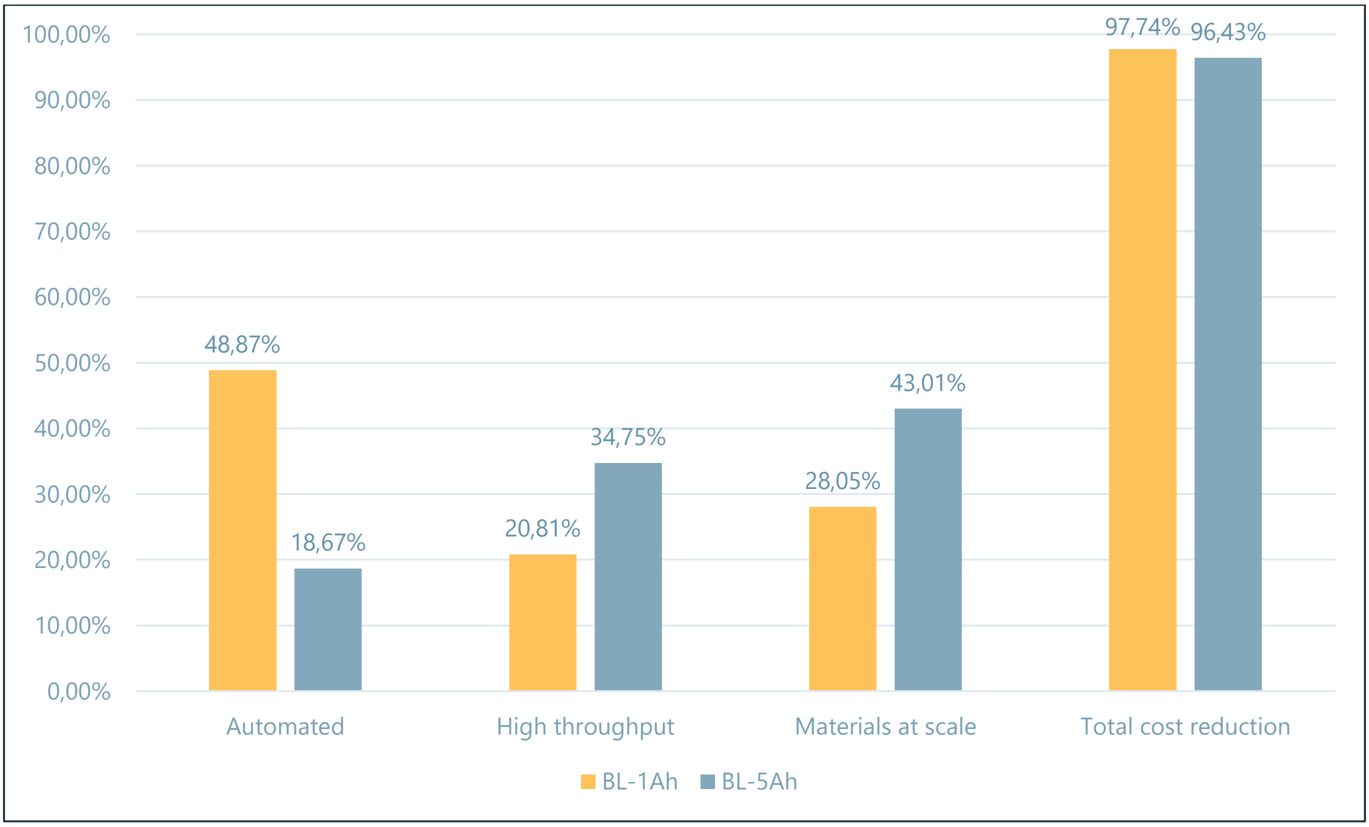

Figure 4. Cost reduction of BL cells.

Borrowing from the semiconductor industry, where similar printing and deposition techniques are used, the sensor production at industrial scale should also benefit immensely from economies of scale. As such, taking a moderate cost reduction of ~30%, the price of L2 and L1 prices, drop to 6.8 €/sensor and 129.9 €/sensor. Finally, all the above bring the cell costs down to the values presented in Table 7.

Table 6. Total cost for SENSIBAT cells produced at scale.

SENSIBAT battery cell	Cost	Units	Cost	Units
BL-1Ah	4.0	€/cell	133.3	€/kWh
BL-5Ah	19.6	€/cell	108.1	€/kWh
L2-1Ah	7.3	€/cell	140.1	€/kWh
L1-5Ah	131.8	€/cell	238.0	€/kWh

6 Benefit Analysis

The internal temperature and pressure sensing, which L1 sensors offer, would be of much use from the safety point of view. Nevertheless, their use would benefit other aspects like:

- Prototyping of battery cells could be benefited immensely as SENSIBAT L1 sensor would allow for a narrow localisation of temperature hotspots and pressure differences in the cell stack, before any catastrophic failure, allowing for a better understanding of the cell operation. This would in turn, shorten the feedback loop and allow for an accelerated prototyping, not to mention a faster time-to-market.
- It will allow EVs to increase charging power and maintain it for longer periods of time measuring the volume changes and internal temperatures.
- New thermal management strategies will be developed when measuring the inside temperature distribution of each cell with both time and space resolution, enabling the detection of local hotspots in an early stage.
- The internal cell pressure evolution will allow to develop a new State of Safety concept making batteries safer.
- Adapted and more accurate BMS state algorithms linked to internal pressure measurement.
- Increased lifetime because of better temperature and pressure management.

The details of L1 sensor-based state algorithms and their benefits are analysed in detail in the deliverable D4.4.

The inclusion of L2 sensors can be justified by better potential control of each electrode:

- Control the balancing of the electrodes while producing the cells.
- Additional range by optimal capacity use.
- Allow improved performance (for example, controlled fast charge and discharge) and safety characteristics of each individual cell. L2 sensor mitigates any safety issues such as overcharging or discharging effects that lead to degradation. For example, it was observed that at higher C-rates, the negative electrode operates in a wider potential window and especially for the 3C rate cycle the negative electrode of the SENSIBAT L2-1Ah cell is threatened to meet potentials close to metallic lithium deposition.
- Adapted and more accurate BMS state algorithms. Mainly linked to SOH estimation based on electrode potential window analysis.
- Higher economic value of cells for 2nd life usage will be possible due to a better understanding of the cell historical behaviour.

The benefits of introducing reference electrodes in lithium-ion cells, L2 sensor, is deeply discussed in deliverable D3.5 and D4.5.

7 Cost Benefit Discussion

In the pursuit of optimizing battery performance and enhancing safety protocols, the integration of sensors in li-ion batteries emerges as a pivotal advancement. The following sections examine the substantial advantages that these sensors afford, thereby altering the landscape of battery innovation within the scientific realm.

The final normalized cell costs are 133.3 €/kWh and 108.1 €/kWh for BL-1Ah and BL-5Ah, respectively. This is in line with the market prices for NMC-graphite cells. With the addition of L2 and L1 sensors, the price of the cells increases to 140.1 €/kWh and 238.0 €/kWh, respectively.

7.1 L1 sensor

The incorporation of L1 sensors entails a pronounced cost escalation (~120%), which makes them non-competitive for commercial exploitation in operational battery cells, although the sensor costs used in the calculations are current lab-scale costs and producing at a larger scale would reduce the costs, it will be needed to adopt different strategies to lower the sensor price.

Assuming a cycle life of 3000 useful cycles (i.e., 80% SoH) for commercial graphite - NMC622 battery cells, the per-cycle cost of such a cell would be 0.08 EUR/kWh/cycle, which limits their application to high-end applications where the performance of the batteries takes precedence over their cost, such as luxury vehicles and eVTOLs.

Alternatively, the cost can be dropped under 0.08 EUR/kWh/cycle by implementing different strategies:

- Optimal implementation of L1 sensorized cell in a module (for example, every two-three cells).
- Simplify the sensor matrix by reducing the number of pressure points.
- Explore combinations with external sensors.
- Scalability to higher capacity cells, such as 100 Ah cells, may also further drive down the cost per energy unit.

Although L1 sensors come with a high cost, they can immensely benefit batteries for high-end application by enabling higher charging power, more accurate state algorithms, longer cycle life and lifetime (all due to precise temperature and pressure control).

Although at this moment, it is difficult to quantify the benefit of L1 sensors, it is clear that due to their high cost and the need of dedicated read-out electronics hampers their massive implementation. At this point, a distinction should be made between the use of L1 sensors in research and development (R&D) versus industrial applications in cost calculations and benefit determination, as L1 sensor implementation biggest benefit could lie in assisting the production of battery cells and modules. In R&D settings, sensor costs are less relevant and L1 sensors may offer significant utility. L1 sensors offer the promise of shortening the development cycle of cells and modules, since when implemented in prototypes Is they would allow for a narrow localisation of temperature hotspots and pressure differences in the cell stack or modules before any catastrophic failure, allowing for a better understanding of the battery operation. This would, in turn, shorten the feedback loop and allow for accelerated prototyping, not to mention a faster time-to-market. By shortening the development cycle of cells and modules, the L1 sensor also contribute to the lowering of the production costs of battery cells.

Therefore, their use can be seen as very beneficial in the battery cell and modules research and development, especially of innovative cell or module designs and chemistries.

7.2 L2 sensor

The inclusion of L2 sensors indicates a paradigm shift in battery technology. Despite a nominal increase in cell costs (~5%), the dividends derived are substantial. L2 sensors empower precise potential measurements, composing a group of data full of advantages:

- Enhanced electrode balancing during cell production.
- Optimized capacity utilization, extending cycle life.
- Enhanced performance and safety parameters, mitigating risks such as overcharging and lithium plating.
- Refined BMS state algorithms, facilitating accurate SoH estimations.
- Augmented economic value for second-life applications, driven by a deeper understanding of historical cell behavior.

As mentioned before, the L2 sensors increased the cell price by ~5%. However, assuming the same 3000 cycles as above, L2-1Ah cells must reach at least 3150 cycles to reach a 0.05 EUR/kWh/cycle cost parity. Any further increase in cycle life, will lower the total cost of ownership of L2-1Ah cells even more, giving them a considerable cost advantage over NMC622 cells without L2 sensors. Due to their configuration, L2 sensors can be seamlessly introduced in the existing battery cell production methods and their low cost allows for their use in each and every battery cell, while providing immense benefits.

In essence, the integration of both SENSIBAT sensors heralds a new era of battery innovation. Not only do they elevate performance benchmarks and fortify safety protocols, but they also democratize access to advanced technology. As we navigate the dynamic landscape of battery technology, sensor integration emerges as a cornerstone of progress, propelling us towards a sustainable and electrified future [12].

8 Conclusion

The cost analysis conducted herein was based on a bottom-up approach, where the bill of materials was used as a starting point to estimate BL-1Ah, BL-5Ah, L2-1Ah and L1-5Ah battery cells at a pilot- and industrial-scale production. It was concluded that the addition of L2 sensors doesn’t increase the cost of the cells considerably, making them suitable for market deployment and offering the opportunity to further drive down the cell cost by increasing their useful cycle life. Direct inclusion of L1 sensors, however, results in cells that are too expensive. Nevertheless, their use finds place in battery development where they can be used to quickly identify temperature and pressure anomalies that could result in catastrophic failures down the line. Therefore, they offer the promise of shortening battery development cycles which could ultimately lower their cost.

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Project partners

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4	FHG	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	Germany
5	FM	FLANDERS MAKE VZW	Belgium
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