Operando Nanoplasmonic sensing – a means of improving battery control – WP2 Report

ACES Project

Adaptive Control of Energy Storage

Final Version

Insplorion AB
2021-03-12

INTERNAL REFERENCE:

Deliverable name	Work package 2 report
Author(s):	Christian Sundvall (Insplorion AB) Elin Langhammer (Insplorion AB)
Reviewer(s):	Ivan Löfgren (WSP Sverige AB) Adam Holmer (WSP Sverige AB) David Westerlund (Embriq AS)
Lead Partner:	Metrum Sweden AB
Document (File):	ACES_WP2_sub_report_final
Issue (Save) date:	2021-03-10
Confidentiality (TLP):	**COLOR - WHITE**

DOCUMENT SENSITIVITY

☒	**Not Sensitive**	Contains only factual or background information; contains no new or additional analysis, recommendations or policy-relevant statements
☐	**Moderately Sensitive**	Contains some analysis or interpretation of results; contains no recommendations or policy-relevant statements
☐	**Sensitive**	Contains analysis or interpretation of results with policy-relevance and/or recommendations or policy-relevant statements
☐	**Highly Sensitive Confidential**	Contains significant analysis or interpretation of results with major policy-relevance or implications, contains extensive recommendations or policy-relevant statements, and/or contain policy-prescriptive statements. This sensitivity requires SB decision.

VERSION MANAGEMENT

Version	Status	Date	Changes
0.1	Draft	2020-08-21	Draft composition
0.2	Draft		Amended and completed chapters 3 and 4
0.3	Draft	2020-12-03	Draft submitted for review

0.9	Final draft version	2020-12-16	Comments from review addressed. Chapters 5, 6, and 7 populated.
1.0	Final draft version	2020-12-17	Populated remaining sections; addressed external and internal review comments; document contains no data and thus very little results and conclusions.
2.0	Final version	2021-02-19	Added data, results and conclusions.

TRAFFIC LIGHT PROTOCOL (TLP)[1]

The Traffic Light Protocol (TLP) was created by the UK Centre for the Protection of National Infrastructure (CPNI) in order to encourage greater sharing of information. In order to encourage the sharing of sensitive (but unclassified) information, however, the originator needs to signal how widely they want their information to be circulated beyond the immediate recipient, if at all. The TLP is based on the concept of the originator labelling information with one of four colours to indicate what further dissemination, if any, can be undertaken by the recipient. The recipient must consult the originator if wider dissemination is required.

Sharing of information is classified with four states (colours). The four colours and their meanings are:

RED	**Personal distribution for named recipients only** Information is shared in the context of a meeting, for example. RED information is limited to those present at the meeting. In most circumstances, RED information will be passed verbally or in person.
YELLOW	**Limited distribution** The recipient may share YELLOW information with others within their organisation, but only on a 'need-to-know' basis. The originator may be expected to specify the intended limits of that sharing.
GREEN	**Community wide distribution** Information in this category can be circulated widely within a particular community. However, the information may not be published or posted on the Internet, nor released outside of the community.
WHITE	**Unlimited distribution** Subject to standard copyright rules, WHITE information may be distributed freely, without restriction.

---

[1] RULES OF PROCEDURE FOR THE EUROPEAN FORUM FOR MEMBER STATES (EFMS) ON PUBLIC POLICIES FOR SECURITY AND RESILIENCE IN THE CONTEXT OF CRITICAL INFORMATION INFRASTRUCTURE PROTECTION, Version 3.0 FINAL – May 2011 "Traffic Light system"

ABSTRACT

Introduction

This WP report explores the potential for equipping lithium-ion battery cells with integrated internal sensors for improved state estimation and operation. As battery control systems continue to evolve and new battery operating strategies are being formulated based on acquired data, the disconnect between physicochemical cell characteristics and externally measured parameters (voltage, current, temperature, etc.) becomes increasingly evident. Furthermore, the lack of accurate estimate of the battery state results in overdesigning battery management systems to manage uncertainties in battery state-of-charge (SoC) and state-of-health (SoH), thus underusing the cell's capability. Could integrated sensors play a part in obtaining truly dynamic battery management?

Background

Insplorion, a Chalmers-based spin-off company, develops and markets their proprietary Nanoplasmonic Sensing (NPS) technology, which can be adopted to a fibreoptic platform, paving the way for a battery sensor. The battery sensor sensing structure allows for monitoring of the internal physicochemical environment and can therefore be an interesting complement to existing voltammetric and external temperature measurement approaches by providing additional parameters.

Fibreoptics are of sufficiently small dimensions such that they can be inserted into battery cells without having significant impact on cell performance or endanger the safety of the cell. Furthermore, fibreoptics are predominantly made of silica—silicon dioxide—which is electrically insulating, meaning there is no risk of electrical coupling between the sensor and battery cell electrodes. In addition, fibreoptics are also immune to electromagnetic and radio frequency interferences which makes them suitable for batteries in electromobility application.

Methodology

Being an optical measurement technique, the fibreoptic battery sensors can be inserted into battery cells during cell assembly and subsequently externally interrogated. To highlight the value of internal sensors two sets of battery cells were commissioned: one with integrated sensors and one without any sensors. These sets were subsequently installed in ACES Demonstrator 1a for comparison.

In ACES Demonstrator 1a the optical signal from Insplorion's battery sensor was collected with an Insplorion instrument setup, the OKTA instrument, shining light trough the fibreoptic sensor and monitoring the outcome. The optical signal was obtained in parallel with the electrochemical cycling data and could be synchronized using post-processing software.

Results

Measurements were performed on one cell with NPS sensor and one cell without sensor. The electrochemical performance of the two cells was very similar but the cell with sensor had a slightly lower capacity at larger cycling depth and slower C-rates. However, due to the small data set it was not possible to draw any conclusions regarding potential differences between cells with and without sensors.

The obtained NPS data was highly reproducible throughout the cycling of the cell and followed the charge level of the cell. The signal magnitude was found to decrease with cycling depth, most likely correlating with the capacity fading of the cells.

Conclusions

The data in this project shows that Insplorion's NPS battery sensor may be used to monitor the charge state as well as the health (capacity) of battery cells.

Managing Partner:

metrum
Enabled by wsp

Partners:

REJLERS
M.I.N.com Smart Solutions
RISE Research Institutes of Sweden
Insplorion
AVA Glava Energy Center
Fraunhofer IFF

Observers:

KREBS'engineers
ABB
VänerEnergi

This project has received funding in the framework of the joint programming initiative ERA-Net Smart Energy Systems' focus initiative Smart Grids Plus, with support from the European Union's Horizon 2020 research and innovation programme under grant agreement No 646039.

The Research Council of Norway
Swedish Energy Agency
PtJ Projektträger Jülich Forschungszentrum Jülich
Gefördert durch: Bundesministerium für Wirtschaft und Energie aufgrund eines Beschlusses des Deutschen Bundestages
Horizon2020

TABLE OF CONTENTS

1. Acronyms

ACES	Adaptive Control of Energy Storage
ACS	Adaptive Control System
BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
BMS	Battery Management System
DUT	Device Under Test
FCEV	Fuel Cell Electric Vehicle
HEV	Hybrid Electric Vehicle
LIB	Lithium-Ion Battery
MRL	Manufacturing Readiness Level
NPS	Nanoplasmonic Sensing
PHEV	Plug-in Hybrid Electric Vehicle
ROI	Return On Investment
SoC	State of Charge
SoH	State of Health
TCO	Total Cost of Ownership
TRL	Technology Readiness Level
UBE	Usable Battery Energy
xEV	Electric Vehicle (the term encompasses BEV, FCEV, HEV, and PHEV)

2. Introduction

"*Operando* Nanoplasmonic sensing – a means of improving battery control" is written as part of the Adaptive Control of Energy storage (ACES) project.

The Adaptive Control of Energy storage (ACES) project has been performed by a consortium of ten [10] partner organisations: lead partner Metrum Sweden AB (Sweden), Glava Energy Center (Sweden), RISE Research Institutes of Sweden AB (Sweden), Insplorion AB (Sweden), Embriq A/S (Norway), MINcom Smart Solutions GmbH (Germany), Fraunhofer Institute for Factory Operation and Automation IFF (Germany), Krebs engineers GmbH (Germany), VänerEnergi AB (Sweden), ABB AB (Sweden).

The ACES project has received funding from the Swedish Energy Agency, The Research Council of Norway and the German Federal Ministry of Economic Affairs and Energy in the framework of the joint programming initiative ERA-Net Smart Grids Plus, with support from the European Union's Horizon 2020 research and innovation programme.

The overall objective of the ACES project is to develop, implement and test advanced measurement technology and adaptive control algorithms for energy storage systems in order to allow for improved economics of operation. By reaching the project objectives, the ACES project aims to contribute to an affordable 100% renewable power system with smart battery storage solutions using artificial intelligence.

More information on the ACES project can be found on: http://www.acesproject.eu/

PURPOSE

The ACES project has been organized in six [6] different work packages with multiple dependencies and collaborations in-between. The purpose of this very report is to present the findings and conclusions related to project goals of work package 2. In addition, a general description and evaluation of the project execution is given, in order to share not only findings related to the project objectives, but also learnings about project methodology and tools in order to further contribute to the research community regarding successful project design.

GOALS AND RESEARCH QUESTIONS

The goals of work package 2 have been to:

- **Improve the operation window of a battery storage system during its lifetime by monitoring health effects and performance with NPS sensors**
- **Validate health effects of different use scenarios**
- **Compare performance and health of batteries with and without Nanoplasmonic sensors**

This report shall describe how and to what extent the above listed goals have been met. Furthermore, Chapter 6 Discussion shall be used to discuss these goals in a broader context, by relating the findings to the following research questions:

- **How can the ACES project outputs lead to improved management of the states of a battery energy storage system (BESS)?**
- **How can ACES provide a means of compensation for the degradation of the BESS?**

These research questions are inherently interesting to several stakeholders in the power and energy sector value chain. It is today very difficult to accurately measure the states of batteries constituting a BESS and thus it is also difficult to appropriately gauge the impact of—primarily— battery discharge operations throughout their service life. Providing means of improving either of these aspects would be important steps to a clearer picture of the total cost of ownership (TCO) for a BESS. In this project, the Insplorion battery sensor optical signal is not interfacing with the ACS. This partly stems from overall delays in getting ACES Demonstrator 1a up and running, and partly from the scope of the project being limited to direct comparison between cells with and cells without sensors integrated. Thus a connection to the ACS is superfluous.

3. Background information

LITHIUM-ION BATTERIES

Lithium-ion batteries (LIBs) have become a reusable energy storage unit of choice for various applications, ranging from consumer electronics to the automotive industry, much thanks to their high energy density[2], high power density[3], and long service life[4]. In recent years, the battery industry has seen a surge in investments, leading to substantial ramps in production capabilities and impressive technological progress. However, even though the price of LIBs has dropped by nearly 90% since 2010[5] it remains one key aspect preventing widespread implementation in applications such as automotive and energy storage. The expensive nature of LIBs is multifaceted and partly stems from the cost of raw materials and manufacturing, electronics, and use of solvents and other chemicals requiring non-aqueous processing. Another aspect which increases the battery price in terms of €/kWh is the limitations placed on the usable battery energy (UBE). Because LIBs are complex electrochemical systems, with interiors sensitive to atmospheric conditions, and because of our innate inability to accurately verify the internal states of the battery cells using our conventional voltammetric characterization techniques, certain parametrical restrictions are placed on how batteries are operated. This includes fixating charge/discharge rates and voltages applied[6], as well as limiting the amount of energy that can be extracted from the batteries—the UBE—manifesting in a state of charge (SoC) window spanning considerably less than the theoretical 100 %[7].

---

[2] Li M, Lu J, Chen Z, and Amine K. 30 Years of Lithium-Ion Batteries. *Adv. Mater.* 2018, **30**, 1800561.

[3] Nitta N, Wu F, Lee JT, and Yushin G. Li-ion battery materials: present and future. *Materials Today* 2015, **18**(5): 252-264.

[4] Blomgren GE. The Development and Future of Lithium Ion Batteries, *Journal of The Electrochemical Society* 2017, **164** (1) A5019-A5025.

[5] Bloomberg New Energy Finance, „Battery Pack Prices Fall As Market Ramps Up With Market Average At $156/kWh In 2019" (2020-06-10), https://about.bnef.com/blog/battery-pack-prices-fall-as-market-ramps-up-with-market-average-at-156-kwh-in-2019/

[6] Wik T, Fridholm B, Kuusisto H. Implementation and robustness of an analytically based battery state of power. *Journal of Power Sources* 2015, **287**: 448-457.

[7] Raghavan A. et al. Embedded fiber-optic sensing for accurate internal monitoring of cell state in advanced battery management systems part 1: Cell embedding method and performance. *Journal of Power Sources* 2017, **341:** 466-473.

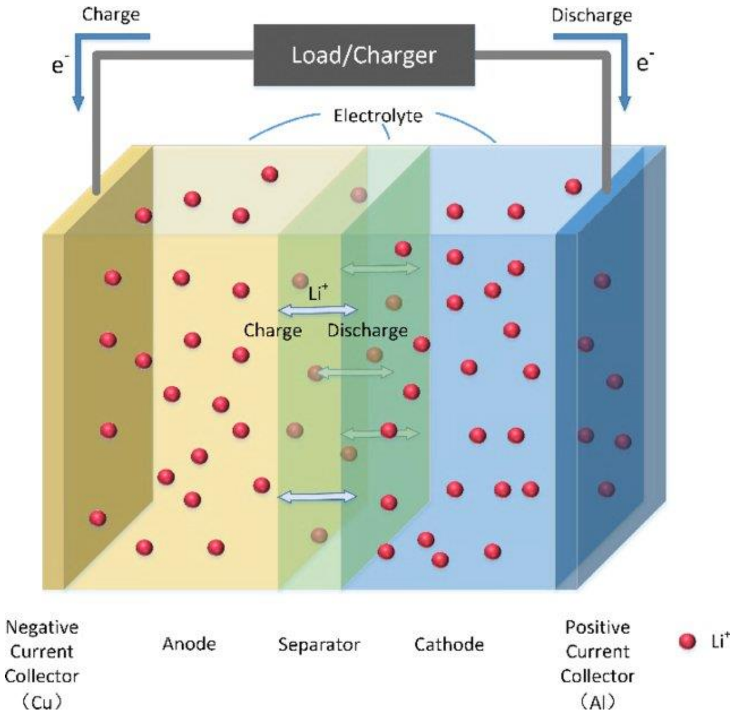

Figure 1: A Li-ion battery schematic, showing the principal components and operation of the cell.[8]

Owing to these considerations, a state-of-the-art battery management system (BMS) must *estimate* battery SoC using inaccurate measurements, assumptions, and complex models[9]. In order to achieve a truly *dynamic* battery management approach we would require *internal* data and signals to be provided—a challenging task considering the small dimensions and harsh internal environment of LIB cells, as well as the demanding requirements on manufacturing. However, one promising candidate for the monitoring of internal processes of LIBs could be the battery sensors based on Insplorion's proprietary Nanoplasmonic sensing (NPS) technology.

NANOPLASMONIC SENSING (NPS)

NPS is a technology for optical measurements developed at Chalmers University of Technology and later patented and commercialized by the spin-off company Insplorion AB. NPS is a surface-sensitive measurement technique. It works by means of metal nanostructures, deposited on a substrate, that act as optical antennae. Incident electromagnetic radiation—light—induces resonant oscillations in the electronic structure of the metal nanoparticles, and the peak wavelength at which these resonant oscillations occur shifts with changes in the optical properties of materials in the close environment of the nanostructures, see Figure 2 for a schematic illustration. By monitoring how the light-material interaction changes with time it is possible to track physicochemical processes occurring next to the sensor.

---

[8] Credit: Zhang J *et al*. An Overview on Thermal Safety Issues of Lithium-ion Batteries for Electric Vehicle Application. *IEEE Access,* 2018, **6**, 23848-23863

[9] Chaturvedi NA, Klein R, Christensen J, Ahmed J, Kojic A. Algorithms for Advanced Battery-Management Systems. *IEEE Control Systems* 2010, **30**(3)**:** 49-68.

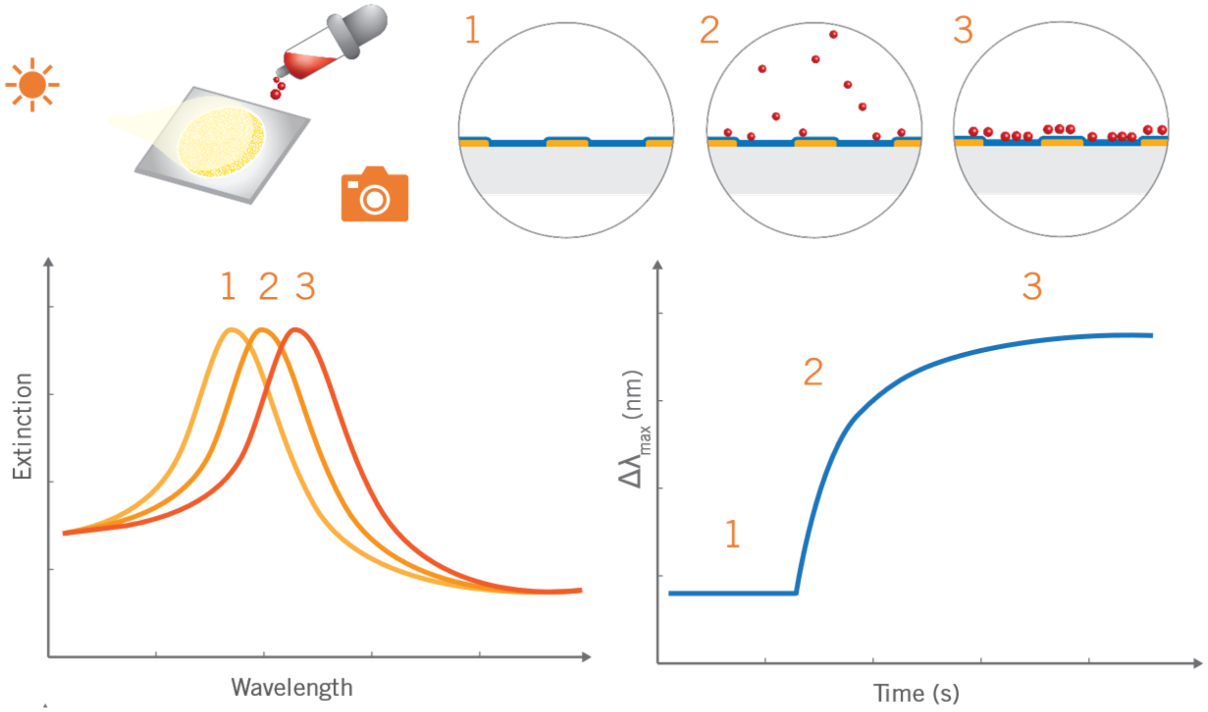

Figure 2: Schematic illustration of how, by the introduction of an analyte, a change in the environment close to the nanostructures, induces an optical shift in Nanoplasmonic Sensing (NPS). (Top) Schematic illustration of analyte molecules adsorbing at the NPS sensor surface. (Bottom left) The plasmon resonance shifts to a longer wavelength when the analytes adsorb on the sensor surface causing an increase in the refractive index in the nanoparticle close environment. (Bottom right) Plasmon resonance peak position as a function of time during the experiment schematically depicted above.

The NPS technology has been implemented by Insplorion in high-end research instruments sold primarily to academic researchers in the fields of life-science, biology, and biotechnology since the founding of the company in early 2010. The research instrument line-up shows the versatility of the technology; that it can be used for gas, liquid, and solid phase reactions. Insplorion has expanded on the capabilities of the technology by developing an expertise in coatings for the sensor structures, providing specificity towards certain analytes, paving the way for the first large-volume product: the NO_2 sensor.

Insplorion's NO_2 sensor is first out in the gas sensor line-up and provides insight into how a high-end and complex measurement setup designed for versatility can be transformed into a sensitive, robust, and specific, yet affordable monitoring system for a certain analyte; a pathway also of interest for Insplorion's battery sensor, hydrogen sensor and other sensor applications.

Whereas in Insplorion's research instruments and gas sensor line-ups the sensor structure is deposited on planar substrates, something different is needed to allow for insertion into LIB cells. The platform that has turned out to be perhaps the most suitable is an optical fibre. Made from silica, i.e. glass, the optical fibre is electrically and chemically inert, small enough to conform to the requirements of the battery cell, and able to act as waveguide for the sensor. Fibreoptics is also a well-known industry and there is a multitude of ways of tailoring the optical fibre to match the intended environment, from fibre diameter to coating providing chemical and mechanical stability.

By inserting an optical fibre equipped with the NPS structure into battery cells and interrogating it with external optical equipment, an opportunity arises to provide BMS with supplementary, internal data. This data may be used to complement pre-existing sources of input such as current, voltage, and temperature—all currently measured externally—providing a possible pathway to truly dynamic battery management.

4. Methodology

OPTIMIZATION OF FIBREOPTIC SENSOR

In preparation for insertion of the fibreoptic sensor, an optimized optical fibre was custom made by RISE (Research Institutes of Sweden) in Hudiksvall. The optimization was done with the explicit purpose to obtain something that is (i) small enough to have minimal impact on the cell stack, (ii) large enough to enable handling for manual sensor insertion into cells, and (iii) has an optical fibre coating which provides mechanical stability and chemical protection.

After the sensing region had been prepared a thin polymer coating was deposited onto the sensing region. This was a precautionary step carried out to protect the now exposed part of the fibreoptic sensor against any potential evolution of hydrofluoric acid inside the battery cell, as the acid could damage the sensing region.

DEVELOPMENT OF OPTICAL INTERROGATION SYSTEM

To enable optical interrogation of multiple fibreoptic sensors simultaneously, Insplorion developed an eight-channel measurement system referred to as the *OKTA* system, seen schematically in Figure 3. The system comprises two components: Insplorion's pre-existing *Optics Unit*, which houses a light source and a spectrometer, and the *OKTA Unit*. The *OKTA Unit* holds a fibreoptic switch, through which light can be coupled from the *Optics Unit* into specific cells and subsequently back into the *Optics Unit*.

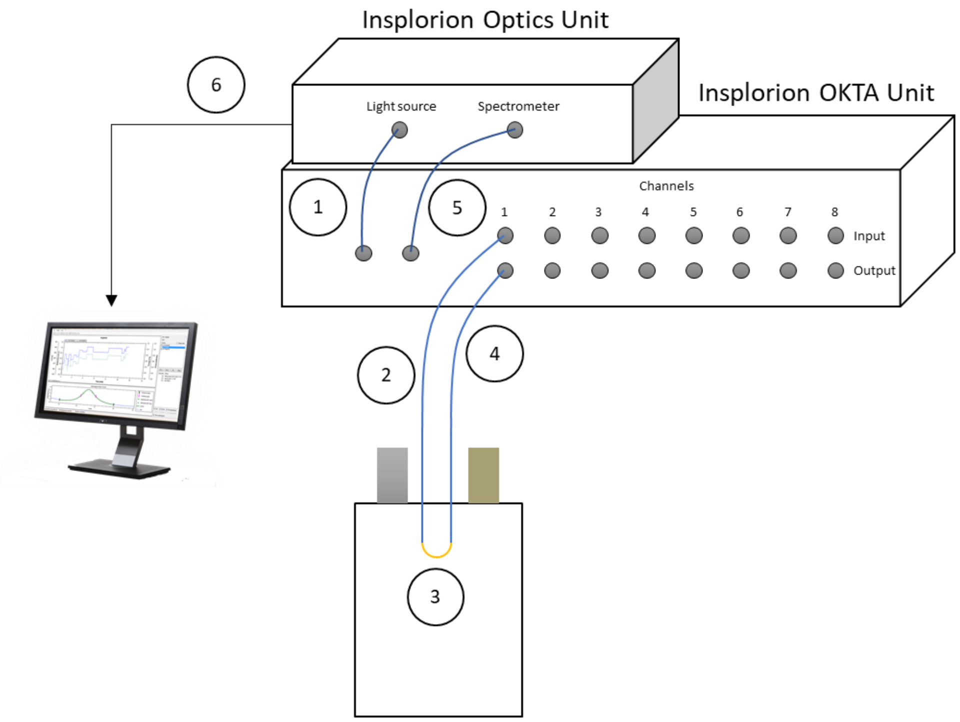

Figure 3: Illustration of the optical interrogation system showing how light is generated (1), coupled into a battery pouch cell (3), fed to a detector (5), from which a digital signal is generated (6).

Thanks to funds contributed by project partner RISE, a piece of control software to run the system and acquire the optical data was commissioned. One *OKTA* system was subsequently provided to the ACES Demonstrator 1a, where it was installed next to the DUT.

DEMONSTRATORS

To visualize the benefits of equipping battery cells with NPS-based battery sensors, production of two different LIB packs, Pack A and Pack B, were commissioned from UK based AMTE Power Ltd (formerly AGM Batteries Ltd.) for ACES Demonstrator 1a, a small-scale demonstrator on the Fraunhofer IFF premises in Magdeburg, Germany.

In the interest of reducing project spending, the LIB pouch cells, shown schematically in Figure 3, implemented in this small demonstrator were selected to be single-layer pouch cells, meaning considerably lower battery capacity (measured in the unit ampere hours, Ah) compared to typical batteries commonly employed in BESS or xEV applications but still sufficient to demonstrate proof-of-principle. The manufacturing procedure of the sensor-equipped LIB cells involved manual steps in AMTE Power's semi-automatic production line.

While both battery packs each consist of 8 lithium iron phosphate/graphite (LFP/Gr) pouch cells, only cells of Pack A underwent the procedure of having battery sensors inserted during manufacturing. The two battery packs would then undergo the same charge and discharge cycles, with the battery sensors expected to have negligible impacts on the cells of Pack A, and a comparison between the two would show how an extra output signal was made available. Direct comparisons between Packs A and B are crucial to validate the added benefits obtained with the NPS sensors.

For the battery sensor, insertion into the pouch cells occurs just before the electrolyte is added. Finally, a specially configured piece of equipment ensures the pouch is tight and sealed such that the battery sensor optical fibre remains intact while at the same time retaining the structural integrity of the pouch cell.

At the ACES Demonstrator 1a, the battery sensors integrated into cells of Pack A were connected to the external optical interrogation system. This was done by means of either fusion splicing, where a high-voltage arc is used to fuse two ends of optical fibre, or mechanical splicing, where the two fibre ends are brought into physical contact so that light propagates from one fibre to the other. This allows Insplorion's battery sensor to be inserted into the pouch cells without a connector present, something that facilitates the assembly process. The interrogation system was previously described in the section *Development of optical interrogation system*. The *Optics Unit* and the *OKTA Unit* were both connected to a PC running Insplorion's control software where parameters of the optical signal interrogation are specified, and which enables recording of the output data.

DATA COLLECTION

Both battery Packs A and B were connected to electrochemical cycling equipment, details of which are available in the WP4 section pertaining to ACES Demonstrator 1a. Charge and discharge operations were carried out in the same manner on battery cells of Packs A and B according to pre-set routines, irrespective of the NPS signal interrogation. These charge and discharge routines were chosen such that it should be possible to both accurately determine the capacity of the cells, e.g. through the process of Coulomb counting, and to also simulate real life utilization, i.e. how battery cells used in a BESS environment might actually be cycled.

Current and voltage ranges for the cycling was determined by the cell specifications: the voltage window was specified to 2.5 to 3.65 V, and the maximum applied and extracted current was specified to 0.5 A. Since it is a prototype cell and the cell chemistry has a sharp quadratic characteristic, the voltage window for the test cycles was set between 2.8 and 3.6 volts. The cycling routine was as follows:

I. Five slow and periodic charge and discharge cycles using Constant Current (CC) at a rate of 1C. This means it takes one hour to charge the battery and one hour to discharge it.

II. Five slow and periodic charge and discharge cycles using CC at a rate of C/2. This means it takes two hours to charge and two hours to discharge the battery.

III. Five slow and periodic charge and discharge cycles using CC at a rate of C/3. This means it takes 3 hours to charge and 3 hours to discharge the battery.

The step-wise cycling protocol of the cycling routines can be found in Table 1.

Table 1: The protocol used the cycling for ACES Demonstrator 1a.

Step	Type	Mode	C-rate	Voltage cut-off	Number of repeats
1	Charge	CC	1C	3.60	5
2	Discharge	CC	1C	2.8	
3	Charge	CC	C/2	3.60	5
4	Discharge	CC	C/2	2.8	
5	Charge	CC	C/3	3.60	5
6	Discharge	CC	C/3	2.8	

The optical data acquired by the Insplorion *OKTA* system was saved as .txt files for post-processing.

Both cycling equipment and optical acquisition software were run from the same PC but are independently collected. Time stamps allowed for synchronisation of the data.

WORK PROCESS

After being connected to the ACES Demonstrator 1a the acquisition process could begin. The electrochemical data and the optical data generated according to the procedure described above were imported to Matlab, where the data sets were synchronized and interpolated to facilitate visualization and enable data analysis. The light extinction at 750 nm was used to correlate the optical response with the electrochemical data. Extinction is the light lost—by absorption and scattering—going from light source to detector. As the nanoplasmonic resonance shifts (Figure 2) the extinction of light at any wavelength, located in the resonance region, will change. The data was referenced to that at the start of charge of each cycle.

5. Results

DISCLAIMER

During transportation of the sensor-equipped LIB cells to the ACES Demonstrator 1a site in Magdeburg, Germany, the shipping company reported an event in which the packaging was damaged. This event is the likely reason for why, when the cells arrived to the site of Demonstrator 1a, the NPS sensors, on the outside of the cells, had been damaged on all but one cell. All cells and NPS sensors were intact before leaving the manufacturer's site in the UK and were well packed. This points to the shipping incident being the cause of the broken sensors. Unfortunately, due the COVID-19 situation and lockdowns in UK it was not possible to make new cells for shipment to Magdeburg before the end of the project.

Therefore, only one sensor-equipped cell could be used for evaluating the internal NPS sensor, severely limited the amount of data acquired in this aspect of the project. In addition, the sensor in the one cell that was possible to connect to the optical readout unit had a very low light throughput, most likely due to a partially damaged sensor.

COMPARE PERFORMANCE AND HEALTH OF BATTERIES WITH AND WITHOUT *IN SITU* NANOPLASMONIC SENSORS

As previously indicated by initial experiments, the battery sensor dimensions were chosen to be small enough such that the sensor has no significant impact on battery performance. This was achieved through the optimized optical fibre developed, as mentioned in the report segment *Optimization of fibreoptic sensor*. Comparing the electrochemical data (voltage and current) for the battery cell with sensor and one without sensor (reference cell) showed that the two cells had very similar Coulombic efficiencies (C.E., Figure 4a). The Coulombic efficiencies are close to 100%, which indicates that there are no parasitic reactions (for instance from electrolyte decomposition) nor lithium plating taking place in either of the cells. This hints to the chemical passivity of the sensor in the battery cell environment. The capacities for the two cells throughout the cycling series are given in Figure 4b. In Table 2 the capacities of the two cells during the last cycles at each C-rate are given together with the relative difference between the two cells (last row). At the fastest C-rate (1C) the cell with sensor had a slightly larger capacity than the reference cell. However, at larger cycling depths and slower C-rates (C/2 and C/3) the reference cell had a larger capacity than the cell with sensor. However, due to the unfortunate events that didn't allow for cycling of more than one cell of each kind it is not possible to determine if this is a significant effect or just a single observation.

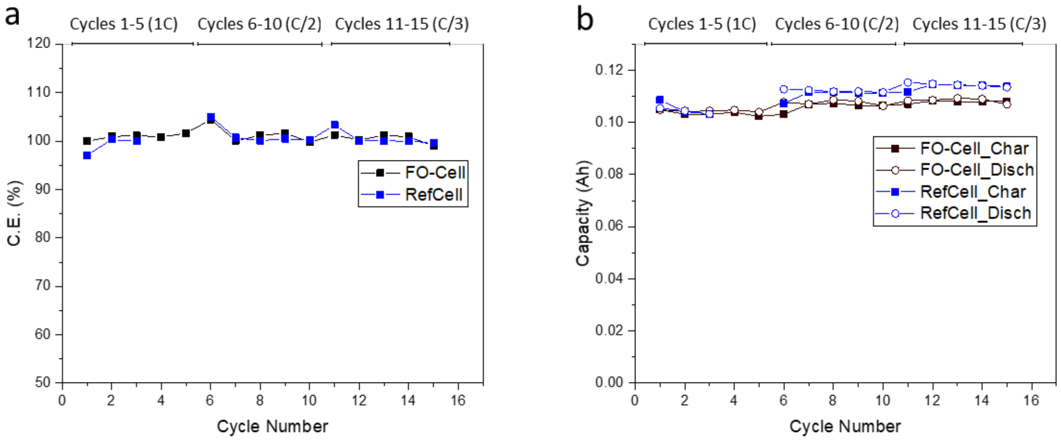

Figure 4: Comparison between the cells with and without sensor. a) Coulombic efficiency. The two cells have very similar Coulombic effiencies. b) Capacity. The cell with sensor has a slightly lower capacity than the cell without sensor.

Table 2: Capacity of the cell with sensor and the reference cell. The capacity values give are for the last cycle at each C-rate.The last row gives the relative difference in capacities between the reference cell and the cell with sensors.

	Capacity		
	1C	C/2	C/3
Reference cell (mAh)	103.27	111.62	113.48
Cell with sensor (mAh)	104.05	106.39	106.94
Capacity difference (%)	-0.75	4.68	5.76

IMPROVE THE OPERATION WINDOW OF A BATTERY STORAGE SYSTEM DURING ITS LIFETIME BY MONITORING HEALTH EFFECTS AND PERFORMANCE WITH NPS SENSORS

The NPS data obtained from operando galvanostatic cycling experiment with 1C, C/2 and C/3 is shown in Figure 5. The optical readout is reproducible throughout the measurement and mostly correlates inversely to the cell voltage. The first cycle of each C-rate was found to present a larger optical response. This may be attributed to a change in the strain experienced by the electrode when the cell undergoes a C-rate change or a memory effect, known to occur in the LFP cathode[10]. For the same C-rate, the amplitude of the NPS signal is seen to decrease with the cycling depth. This is most likely due to the capacity fade of the cell.

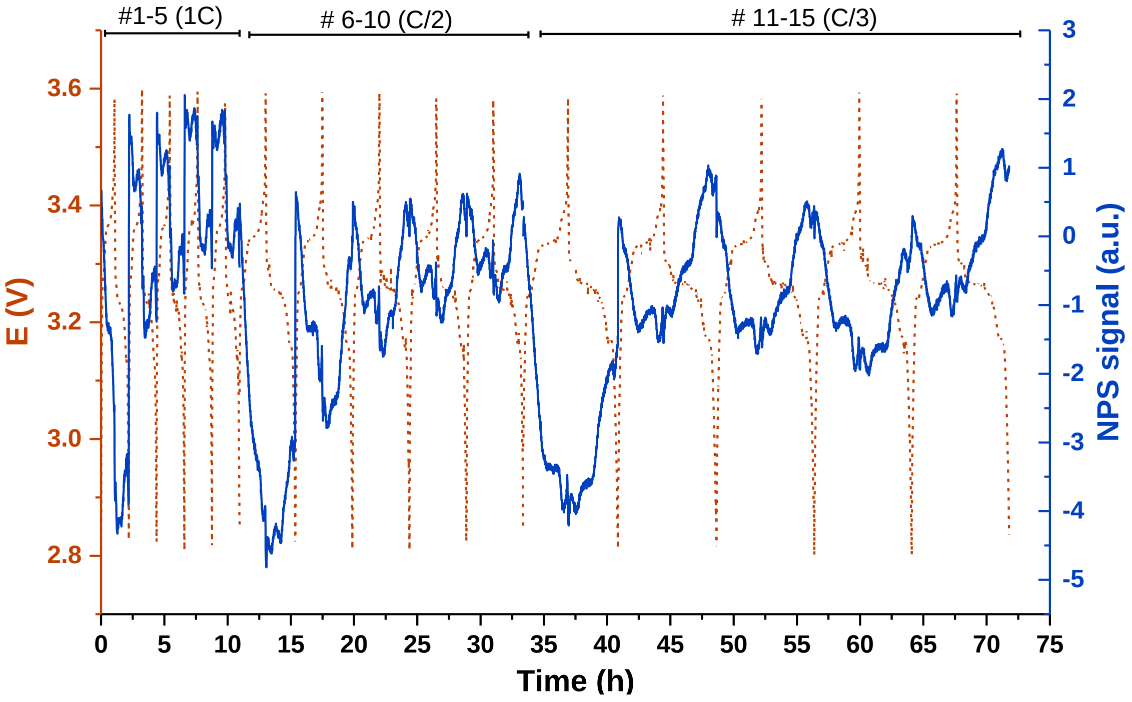

Figure 5: NPS signal correlation with battery performance. Voltage profile obtained in cyclic charge-discharge experiment, comprising 15 cycles. NPS signal obtained by the optic fibre sensor at LFP side in LFP || Gr cell.

---

[10] T. Sasaki, Y. Ukyo, P. Novák, Memory effect in lithium-ion battery, Nature Materials, **2013**, 12, 569–575

In Figure 6, the five cycles at C/2 are compared. It is clearly seen that the NPS signal during the first cycle at this rate is larger than during the consecutive cycles, as discussed above. The NPS signal correlates well with the voltage and is highly reproducible at different cycling depths. There is a slight "drift" in the signal which is most likely due to changes in the electrode material close to the sensor. Previous measurements have shown that this "drift" decreases with cycling depth.

The different lithiation stages, formed with lithium intercalates into graphite, are clearly seen in the signals and are indicated by the shaded areas in Figure 6 (left).

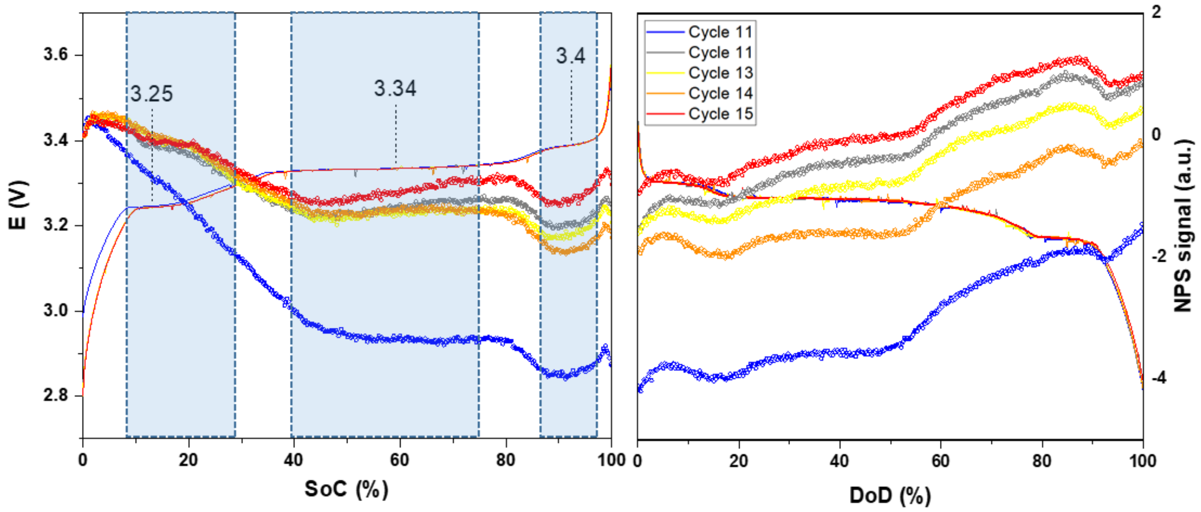

Figure 6: Voltage and NPS signal at C/2 rate, as a function of SoC (left) and DoD (right). Features in the optical signal, shown by the shaded areas during charging, match the plateaus in the voltage curve and are likely related to graphite staging (stage III, II and I at 3.25, 3.34 and 3.4V, respectively).

A qualitative correlation between the optical signal and the capacity of the cell was found. Figure 7 shows that as the C-rate decreases the effective capacity of the cell increases as expected. The NPS signal shows a similar trend with increasing signal for decreasing C-rate. This indicates that the NPS signal can be used to monitor the capacity of cells during use, which is very important since it is the loss of capacity that determines when the batteries need replacing.

Due to the limited number of cycles performed on the cell (a total of 15 cycles at three different C-rates) is it not possible to establish a quantitate correlation of the optical signal to battery state of charge /state of health.

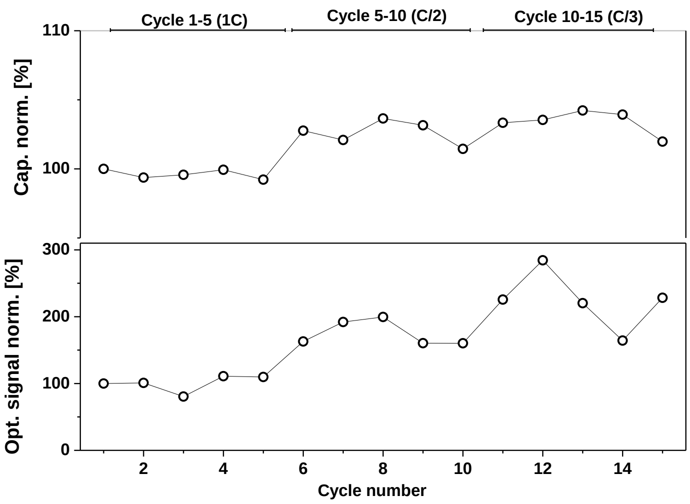

Figure 7: Capacity (top) and normalized NPS signal (bottom) for all cell cycles. The optical signal shows the same trend as the capacity indicating that NPS can be used to monitor the capacity loss.

VALIDATE HEALTH EFFECTS OF DIFFERENT USE SCENARIOS

The cells were to be cycled in a way that should simulate real life use. However, due to the issues with the broken sensors and the limited time available we were unable to perform these tests.

6. Discussion

ON THE OPTICAL SIGNAL

When charging a LIB, the active material in the cathode is oxidized as its lithium is extracted and effectively transported to the graphite anode. In the instance of the LFP cells in this project, it follows the reaction:

$$LiFe(II)PO_4 \leftrightarrow Fe(III)PO_4 + Li^+ + e^-$$

As iron(II) is oxidized into iron(III) upon charging—and inversely reduced during discharging—the dielectric properties of the material changes, which is picked up by the optical interrogation system. The ability to monitor this transition has been demonstrated for embedded evanescent wave sensors using cyclic voltammetry (CV) measurements[11]. Adding the capability of monitoring active material in this fashion to current state of the art battery management systems expands on the models currently used. In turn this could lead to improvements in the operational window available as the system no longer relies solely on cell potential to indicate progression of electrochemical processes.

Furthermore, as the sensor in this instance is not fully embedded in the active material there is also an element of the electrolyte influencing the signal. As the capacity fades

---

[11] Hedman J, Nilebo D, Larsson Langhammer E, Björefors F. Fibre Optic Sensor for Characterisation of Lithium-Ion Batteries, *ChemSusChem*, **2020**, *13*, 5731 – 5739

with time and use, this is also reflected in the overall signal level obtained by the interrogation system. Feeding this into the BMS adds additional information that helps in the forming of a complete picture of the battery state.

CONNECTING TO A BIGGER PICTURE

A next step after setting up the infrastructure and ecosystem to acquire the optical signal is to connect it to the appropriate management system in real time. Whether the signal first links with the BMS or directly interfaces with other control systems like the ACS might be somewhat flexible, as the signal should be able to stand on its own.

Through interfacing with, for example, the ACS, the added signal then expands the pre-existing dataset to better manage a BESS. The signal itself would correspond to a change of internal physicochemical parameters and be supplied live by Insplorion-made hardware and software. However, for the complete state estimation the optical signal would on its own be insufficient. The combined inputs from voltage, current, external temperature, and internal NPS based optical sensor signal would create the basis for improved state estimation and operational control.

TOWARDS SMART*ER* GRIDS

The International Energy Agency (IEA) defines a smart grid as "an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources in that (local) network to meet the varying electricity demands of end-users"[12]. Implementation of smart grids is expected to play an important part in increasing the flexibility of the power grid and energy supply, a key aspect as demand rises and the fraction of generated electricity originates in intermittent renewable energy sources, such as wind and solar. Improving the conditions within which BESS-equipped smart grids operate, by for example developing smart algorithms through machine learning or expanding on the methodologies with which the states of the batteries are gauged, could enable increased reliability and even greater flexibility. With the NPS based battery sensor Insplorion hope to be able to contribute to improved monitoring procedures of battery cells in energy storage contexts, and subsequently facilitate in operations and billing by providing a means of more accurately estimate battery SoC and SoH.

Suppose a BESS in operation has been charged off hours through excess electricity generated by wind turbines to an estimated 50 % SoC. Already at this point the scenario suffers from the fact that there are problems with properly estimating SoC using current methods, something Insplorion want to remedy by providing supplementary information for estimation algorithms to implement, thus **leading to improved management of a BESS**.

Assume, for the sake of argument, that the 50 % SoC estimation is correct and that suddenly the energy storage is requested to assist in a peak shaving operation. Through smart predictive algorithms developed in this project, the energy required to perform the peak shaving operation is predicted to reduce the BESS SoC to 20 %. Now, how expensive would such an operation be for the owner or operator of the storage system in terms of degradation of the battery cells, i.e. how would such an operation impact the SoH of the BESS? This is highly relevant to know as it impacts the ROI. State of Health is a wide term when it comes to batteries and can encompass capacity fade, dendrite formation, electrode cracking, gas evolution, and more. Electrode cracking can be monitored through increased internal resistance of the cells, and there are ways of quantifying capacity fade—which is why it is commonly equated with SoH—but properly estimating the *real* SoH of an LIB cell

---

[12] International Energy Agency. *World Energy Outlook*; Organization for Economic Co-Operation and Development (OECD): Paris, France, 2011; ISBN 978-92-64-12413-4.

is nigh impossible. In this context any new information that can assist in providing a *better* estimation on SoH is welcomed. As such, **Insplorion believes that the NPS based battery sensor can be of value in establishing more balanced arrangements for compensating the owner for the degradation of their BESS**. It would also serve to provide a more complete picture of the investments required. If successful, such circumstances could lead to ownership of energy storage systems becoming more transparent and, by extension, more appealing.

RELATION TO THE THREE-LAYER RESEARCH MODEL FRAMEWORK

Technology

Implementing battery sensors has the potential to impact all technological sectors comprising battery energy storage in some form, be it small-scale smart grids, batteries for local residential storage, large-scale commercial energy storage systems, or ancillary batteries in fuel cell setups. While the technology can be inherently interesting on its own it needs to also provide some benefit to the application to be relevant. It also needs to interface seamlessly with other technologies, such as estimation algorithms and communications protocols, to even be considered a candidate for adoption.

Sensors for batteries are undoubtedly to be introduced to the energy sector at some point and likely internal sensors have capabilities that external sensors cannot fully contend with. However, what kind of sensor, how it is implemented, and in which applications remain to be seen, as these are driven not just by technological advancements and idealized operational strategies but also by the market and stakeholders; a battery sensor doubling the amount of UBE has no future if it sees no acceptance from market and end users.

Marketplace

Insplorion's battery sensor has the potential to provide much needed complementary information to battery energy storage systems constituting anything from smart grids to large container-based battery reservoirs. Improving state estimation and providing supplementary information to further optimize operational strategies are key to achieving truly dynamic management of batteries with greater insights. A more well-controlled ecosystem should be welcomed by most actors in the business and could possibly contribute to boost investments in battery-based energy storage systems due to increased transparency.

On the other hand, market adoption and acceptance are typically driven by cost and ROI. With this in mind it becomes increasingly important that the battery sensor as a technology and—perhaps more importantly—as a product is validated and verified as an addition that brings value enough to warrant the extra investment while simultaneously not jeopardizing the safety or stability of the system. Moreover, even though it is perhaps most important to show that the extra investment for equipping the battery cells with a sensor is worth it in the long run, the actual investment itself must be taken into consideration. To increase the chances of implementation, manufacturing of the battery sensor must be possible to scale up and integration into the cells must be straightforward for the supplier. This becomes increasingly important as the sensor technology move through the TRL and MRLs, from lab-scale to prototype and onwards, and requires continuous dialogue with the relevant actors as well as thoroughly conducted surveys and market studies.

Stakeholder adoption / End-user acceptance

Perhaps the most crucial aspect of the three-layer model, the various stakeholders and end users ultimately decide if a technology will establish itself on the market. The different actors have different priorities and prerequisites which factor into whether they buy into a product or not, and so finding the right stakeholder and end user segment is important. While some prioritize low investment cost some might value operational capacity—being able to push a system to its limits—and such niche actors and early adopters could be the primary target for sensor-equipped battery energy storage. In the ACES project this was addressed—to an extent—by the implementation and hosting of the Reference Group, where actors were invited to learn more about ACES and voice their opinions.

Regardless of stakeholder and end user segment, one key priority is global: safety. If battery cells cannot be shown to be as safe with a sensor equipped as without, it will be extremely hard to gain acceptance in the energy and power industry. While one could potentially find such extreme niche actors in e.g. performance car racing, there are few examples of the equivalent extreme in energy storage.

7. Conclusions

REPORT CONCLUSIONS

The cell with sensor had a similar Coulombic efficiency as the one without sensor but a slightly lower capacity at larger cycling depth and slower C-rates. Unfortunately, it is not possible to determine if the difference is significant due to the very small data set (only one cell of each kind).

The optical signal was highly reproducible throughout the cycling and correlated well with the SoC and DoD of the battery cell. Although the sensor was placed between the cathode and the separator the signal showed signs of the different intercalation stages in the graphite anode. This is most likely due to pressure changes inside the cell. The signal during the first cycle at each C-rate was different than those obtained during subsequent cycles at the same C-rate. This is explained by a change in the strain experienced by the electrode when the cell undergoes a C-rate change or a memory effect, known to occur in the LFP cathode.

LESSONS LEARNED

The project has provided valuable experiences and lessons pertaining to, for example, shipping and transportation of sensor-equipped battery cells as well as integration into systems. Although much of the delay in manufacturing the cells to installation and system booting can be attributed to the ongoing pandemic, aspects such as timing production slots at battery cell manufacturers and preparing sensor fibres for installation are also valid given "normal" circumstances.

Improved dialogue between project partners is—and remains—a key factor in achieving seamless collaboration. While many things worked well in this project certain things, such as the need to adjust system level components and the subsequent effect on the capabilities, were lost or misunderstood, leading to a disparity between projected end results and actual end results.

RECOMMENDATIONS FOR FUTURE STUDIES

Regarding the same system components, the measurement should be replicated with better controls to make sure data is obtained from all cells according to plan. A longer test period would allow to collect more data from each individual cell.

Future work includes increasing cell capacity to better simulate real life applications, further developing the fibreoptic sensor to provide a stronger and more stable signal, improving the preconditions for installing the cells into the system, as well as to interface the optical signal with a BMS or supplied directly to an EMS or ACS.

Work should also be continuously carried out on establishing a dialogue with the stakeholders, end users, and actors throughout the value chain to build a case for the battery sensor. This will have to be backed by data, and so multiple processes must be conducted in parallel to move the subject forward.