Journal of Electronics and Electrical Engineering
https://ojs.wiserpub.com/index.php/JEEE/

Review

Sustainability and Prolonging Rechargeable Battery Life: A Sensor Device Review

Swati Sahu*, and Sanjay Tiwari

Institute of Renewable Energy Technology & Management, School of Studies in Electronics & Photonics, Pt. Ravishankar Shukla University, Raipur, India
E-mail: swati.luck05@gmail.com

Received: 3 April 2023; **Revised:** 10 May 2023; **Accepted:** 11 May 2023

Abstract: Rechargeable batteries have recently experienced increases in productivity and the economy, solidifying their dominance in energy-intensive cultures. Regular performance monitoring is required to lessen the adverse environmental effects of batteries in the face of increased demand. The distinctive features of lithium-ion batteries (LIBs) make them an ideal choice for energy storage. Battery management systems (BMSs) are needed to make sure that LIB systems are safe and operate effectively. Critical problems in the existing structure and operation of BMSs are their limited data storage capacity and weak computational power. This paper studies the idea and architecture of cloud-based smart BMSs and offers some viewpoints on their performance, usability, and advantages for upcoming battery applications. While some of the benefits of sensors have been recognized for more than a hundred years, the combination of diverse sensing technologies with novel battery platforms has the potential to revolutionize the sector by changing how both new and old lithium-ion devices are used. This paper also highlights current advances and their associated benefits focusing on electrochemical, mechanical, acoustic, and optical sensors that can potentially boost battery sustainability and longevity.

Keywords: rechargeable battery, lithium ion-based batteries (LIBs), sensor, fiber optics, battery management system (BMS), state of charge (SoC), state of health (SoH), sustainability, solid electrolyte interphase (SEI)

1. Introduction

Our planet faces severe sustainability concerns that demand cutting-edge research in a range of sectors, including electrochemical battery storage. For the energy transition into a more carbon-neutral world to be successful, there must be a significant advancement in battery technology. In the same way that the electrification of transportation necessitates far more affordable and long-lasting batteries, new storage technologies are required if more renewable energy sources are to be deployed on the electrical grid. Maybe more than any other, rechargeable battery technology best exemplifies the twenty-first century's sustainability issues [1]. Although lithium-ion batteries (LIBs) have largely replaced those that came before them due to the never-ending and complex requirements of many sectors, as well as the growing Internet of Things (IoT) communications boom, lead-acid and nickel-metal-hydride power sources are established technological advances with essentially supply chains that are closed-loop and good components restoration/reusability. During the vehicle's operational life, the integration of such battery packages imposes strict control on the battery's safety status, state of charge (SoC), and state of health (SoH). The battery's "state of health," which is determined by the difference between its actual and initial capacities, predicts the system's anticipated remaining life. It is challenging to accurately and robustly determine the SoC and SoH of the automotive battery package due to cost restrictions and the requirement to reduce complexity [2,3].

DOI: https://doi.org/10.37256/jeee.2120232781

With the increased use of portable electronic devices, electrochemical energy storage technologies, notably lithium and lithium-ion batteries, are pervasive in modern culture. A variety of functional requirements are posed by novel storage applications like the incorporation of renewable energy generation and the increased usage of electric vehicles. Electron and ion transport are essential to battery operation because they control the battery's energy output under application-specific conditions and the amount of overall energy that can be used [4]. Despite climatic change and the decrease in greenhouse gases, EVs have now demonstrated their potential. Power batteries have evolved in recent years into a great energy storage component for EVs. A new thermal problem will emerge in the battery pack of EVs as the need for rapid charging and exceptionally fast charging batteries rises. Therefore, having a strong battery thermal management system (BTMS) is necessary to ensure both safeties as well as outstanding performance [5]. A phase-change material (PCM), metal foam, as well as fins make a BTMS that maintains the battery's surface temperature at the lowest feasible temperature while discharging under both typical and challenging environmental circumstances [6]. Due to its great efficiency and low energy cost, AC pulse heating is a viable preheating technique for lithium-ion batteries. Obtaining the upper bound of the heating current (UBHC) is necessary to prevent lithium plating during AC heating. To estimate the battery temperature and voltage of the negative electrode, Li et al. created a dual RC model that they connected with a thermal model [7].

One of the fundamental tasks performed by a battery management system (BMS) is state estimate. Correct state estimates can increase battery safety and extend battery life. The main obstacles to accurate battery state estimates are, in particular, the scarcity of quantifiable data, the incompatibility of model parameters, extreme nonlinearity, and temporal fluctuation of battery state. Intelligent algorithms, large data, cloud computing, and intelligent sensing are thus workable options. With the help of modern intelligence algorithms to improve the model and signal characteristics, intelligent sensing to get more plentiful signals, cloud computing, and big data mining to thoroughly mine distinctive signals, battery state estimation's accuracy, and stability are gradually improving [8].

Due to qualities like high voltage, prolonged cycling life, as well as low self-discharge, LIBs have become the most popular rechargeable batteries. A LIB is made up of a separator, a negative electrode, a positive electrode, and related current collectors (see Figure 1). Lithium ions alternately move between the cathode and anode during charging and discharging. While the process of charging and discharging, lithium ions transfer between the cathode and anode. When a discharge occurs, ions travel from the anode's surface to the cathode using the electrolyte, while electrons travel from the anode to the cathode via an external circuit. When the battery is charged, ions return to the anode via the electrolyte, while an external force pushes electrons from the negatively charged cathode to the anode end of the battery. Na^{+}, K^{+}, Zn^{2+}, Ca^{2+}, Mg^{2+}, and Al^{3+} are also useful ions, while Li^{+} is the most frequently utilized. The chemistry within a battery varies depending on the working ion utilized, and this must always be kept in mind. As a result, Li-based battery anodes and cathodes cannot be regularly employed in other battery types. In order to evaluate battery performance, electrical characteristics are used as technical operating parameters. When comparing manufacturing specifications, such as capacity, C-rate, nominal voltage, and cycle life, these parameters can be used to describe the current state of a rechargeable battery, such as SoC, SoH and DoC. The amount of charge a battery can store is referred to as capacity, and it is determined by the mass of the active material. When a battery is depleted, its capacity is the total number of Amp-hours (Ah) that are still usable. Voltage, a battery characteristic that describes the variation in potential between the cathode and the anode, is another. Ideal cathodes should have high potentials, and ideal anodes should have low potentials in order to produce high voltages. Battery C-Rates regulate a battery's charge and discharge rates. The measurement of the current at which a battery is charged and discharged is known as the battery C-Rating.

The fundamental electrode process during battery charging and discharging includes electronic conduction, electrode response, solid-phase diffusion, lithium-ion transfer, and diffusion. During battery operation, heat processes and performance degradation also take place in addition to electrochemical behaviors. Although the prospect of higher carbon neutrality and "microeconomic" have an impact owing to increased utilization of LIBs is outstanding it is vital for improving the quality, durability, longevity, and stability of cells and systems [9]. Major research teams and available resources are now concentrating on "promoting green" LIBs [10] with the use of environmentally friendly electrodes and materials, reconsidering resource recovery strategies, and broadening the hunt for passively, non-disruptive diagnostic methods that can observably enhance device efficiency [2]. Additional advancements are needed to solve performance, durability, and cost concerns to realize the full potential of these devices. Current demands on LIBs include increasing power and energy density as well as extending the operational cycle life of batteries for one and only-life applications. In addition, the growing acceptance of battery-powered cars and electric-hybrid automobiles, that employ batteries as a valuable part, calls for significant advancement in the operand expect of the state of health (SoH) and deterioration. Battery monitoring, on the other hand, is a difficult challenge that must be solved by unraveling an inherent conflict between primary and parasitic faradaic biochemical reactions including phase transitions, as well as restrictions on electronic and ionic transport. Lithium plating, electrode fracturing, metal dissolution, shuttle movement of redox pollutants, and uncontrollable expansion of the solid electrolyte interphase (SEI) are a few examples of the phenomena that parasitic reactions can cause [11]. In addition to harming cell performance, all of these phenomena also result in a systematic underutilization of cells and batteries due to weak diagnostic capabilities, which causes an overreliance on faulty data to set safety margins.

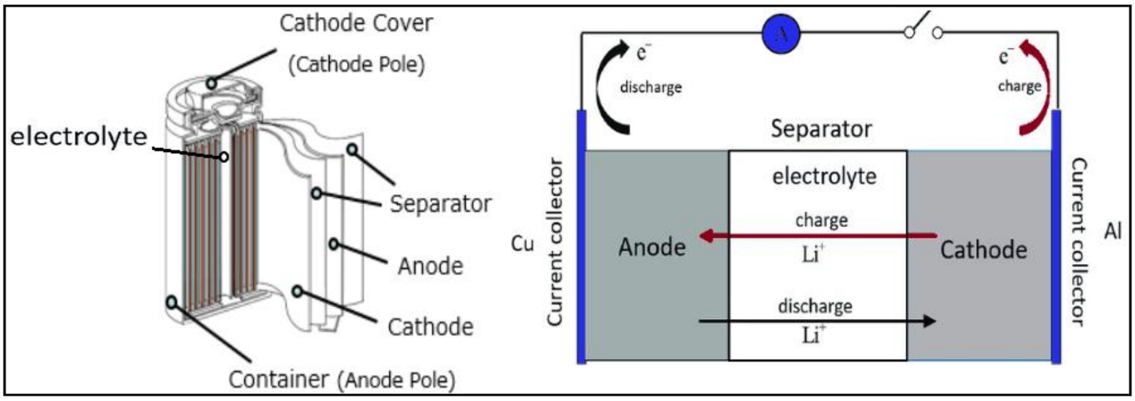

Figure 1. Schematic representation of LIBs/rechargeable batteries.

To understand the basic physics of battery power, which need advanced instrumentation [12–15] and can optimally perform in specific mutations or when a cell is cycled, a variety of characterization methodologies have been established in the lab. Meanwhile, these analytical methods necessitate specialized tools and cell layouts incompatible with commercial cells [16]. Recent battery management systems' primary data components for field monitoring are current, terminal voltage, and impedance characteristics. Unexpectedly, temperature and its slope profoundly regulate the battery chemistry and longevity for electric vehicle (EV) use [17] and are now monitored indirectly at the module scale rather than directly at the individual cell level. Individual-cell sensing with analog temperature sensors is being investigated, but their integration has been impeded by their size and required wiring [18–21]. Battery management system (BMS) units are still limited to estimating dependability and functionality through statistical techniques, even if they have exact knowledge of the cell temperature. A battery for an electric car may cost as much as one-third of the value of the vehicle, therefore the search for high-value information resulting in longer battery service life is warranted, even though such an estimation is suitable for "disposable" devices. With the aid of newly developed cell-level sensors, we should be able to study physical, chemical, and thermal parameters (in particular mutations) with an acceptable time and spatial resolution, leading to significantly more precise estimates of the state of charge (SoC), state of health (SoH), and preliminary reports.

The following sections comprise the remaining text of this review: A summary of several battery-detecting techniques is covered in Section 2. For the sustainable use of rechargeable batteries, Section 3 examines three advanced battery management (BMS) strategies: the BMS comprises safety management, heat management, charging/discharging management, equalization management, safety/ageing management, and fault detection. Section 4 covers the principal Battery sensing techniques: The ability to comprehend the battery better will be made possible by the addition of some smart measurement data on the electrochemical, mechanical, acoustical, and optical characteristics of the batteries. Section 5 concludes the essay by listing the current difficulties, outlining the prospects for future research, and summarizing the paper.

2. Overview of Several Techniques for Battery Sensing

The electrical output of conventional batteries cannot be directly controlled, making them passive sources of power and energy. A typical BMS keeps track of the batteries' functional state (terminal voltage, current, and pack temperature) to evaluate their SoC and SoH and to manage the batteries while they are cycling. Due to the relatively few monitored parameters and incomplete knowledge of cell activity, batteries still face technological challenges in precisely forecasting the states and monitoring the operation, which have a substantial impact on the QRL (Quality, Reliability, and Life) of the batteries. The problems are anticipated to be solved by a powerful battery-sensing system that is simple to use and performs well. Nascimento et al. [22] built a hybrid sensing network into a Li-ion battery pouch cell to measure and distinguish internal strain as well as variations in temperature simultaneously in real-time. For a secure and reliable operation, the results directly gave more accurate information for state estimation. Additionally, the sensing data provided information on the development of heat and stress in the batteries, allowing researchers and engineers to better understand the internal components of the battery and support the creation of novel computer models of the battery's structure. As a result, future battery design will be improved and battery chemistry will advance further. Additionally, battery sensing can demonstrate early performance decline indications.

A statistical analysis of the numerous technologies for sensing included in patents for battery module designs as well as systems was presented by Dominko et al. [23]. Numerous battery sensing methods have been tested over time to look at various battery compositions. As of yet, it has been discovered that optical fibre sensors (OFS), including fiber Bragg grating (FBG), evanescent wave spectral analysis, and other fibre optics, are responsible for the majority. Figure 2 shows the academic trend for battery sensing techniques; the current/voltage sensing methods are not shown since they have reached their advanced research stage. The key sensing techniques being developed to monitor various parameters, including temperature, strain, and SoC/SoH, are listed in Table 1.

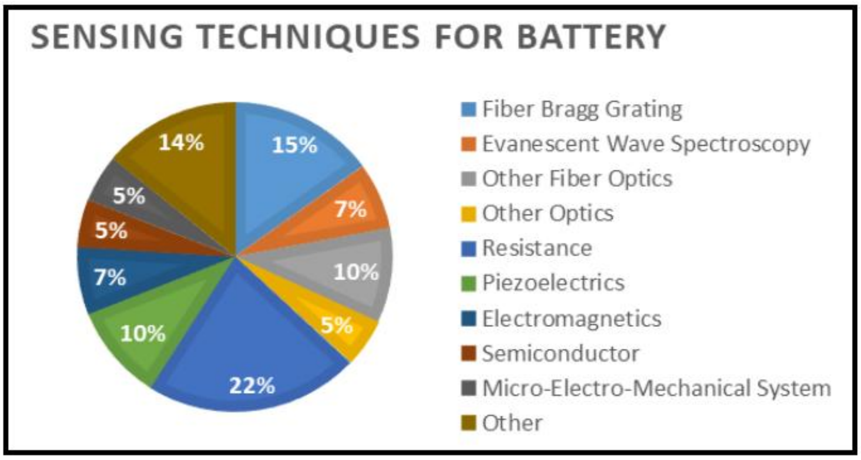

Figure 2. Battery-compatible sensing techniques.

Due to temperature gradients that may cause local variances in battery ageing and, ultimately, worldwide ageing, the temperature is a crucial component in determining batteries' safe and stable operation. A range of temperature-sensing systems for batteries is required because breakdowns, temperature runaway, leakage, combustion, and explosive of batteries might happen under a lack of cooling or extreme temperatures [24]. Thermocouples (TC), thermistors [25,26], and resistance temperature detectors (RTD) [27,28] appear to be well-established methods that are frequently used to track the temperature of the surface across all implementations whereas TC and RTD are more frequently used to monitor the temperature within the device in a laboratory. While they have benefits like outstanding sensitivity, small dimensions, quick response, and inexpensive, they also have drawbacks such as wiring and location concerns that don't affect battery performance. The distribution of surface temperatures as well as areas of heat inside the battery can be observed using two prominent techniques, thermographic imaging [29] and infrared thermal imaging [30], both of which have intricate designs, poor spatial resolution, and limited temperature precision. Furthermore, as separate-point monitoring methods, these approaches are insufficient to obtain the spatially non-uniform temperature distribution. Because the surface temperature is much lower than the actual peak temperature of batteries, the monitoring of the internal temperature is more advantageous and precise for keeping the batteries functioning within the ideal operating temperature range and for raising the QRL of the batteries [24].

Table 1. Several techniques for battery sensing.

Parameter	Technique	Deployment	Destructive potential	Ref
Temperature	Thermocouple (TC)	Both inside and outside	Nondestructive	[47,48]
Temperature	Thermistor	Both inside and outside	Nondestructive	[25,26]
Temperature	Resistance Temperature Detector (RTD)	Both inside and outside	Nondestructive	[27,28]
Temperature	Thermographic Imaging	Outside	Nondestructive	[29]
Temperature	Infrared Thermal Imaging	Outside	Nondestructive	[30]
Strain	Strain-gauge	Outside	Nondestructive	[31]
Strain	Load Cell	Outside	Nondestructive	[33]
Strain	Digital Image Correlation	Outside	Nondestructive	[34]
Strain	XPS (X-ray Photoelectron Spectroscopy)	Outside	Destructive	[49]
Strain	X-ray Diffraction (XRD)	Outside	Destructive	[35]
SoC/SoH	EIS (Electrochemical Impedance Spectroscopy)	Outside	Nondestructive	[38]
SoC/SoH	ECM (Equivalent Circuit Model)	Outside	Nondestructive	[50]
SoC/SoH	Machine Learning Algorithm	Outside	Nondestructive	[39]
SoC/SoH	EM (Electron Microscopes)	Outside	Destructive	[43]
SoC/SoH	Scanning Transmission Electron Microscope (STEM)	Outside	Destructive	[42]
Temperature & Strain & SoC/SoH	Optical Fibre Sensor	Both inside and outside	Nondestructive	[44,45]

Strain is just as crucial to battery regulation as temperature since it results from the buildup of heterogeneous electrode stress, which reduces the capacity and power of batteries [31]. Typically, the electrode stress can be represented by the electrode surface pressure and/or the entire battery and the dimensional change. Using a strain gauge [32], which measures the total volume change of batteries, is the easiest approach to measuring strain. Load cell [33] is a different strain measurement technique that uses a constraint fixture to measure the mechanical stress at the stack level in real-time. An amplified load cell and a battery cell are linked in series to form the constraint fixture. With the help of a series of digital photos and a non-contact optical technique called correlation of digital images [34], strain is directly measured in two or three dimensions by following a recognizable pattern on the surface. Two destructive methods, XPS (X-ray photoelectron spectroscopy) as well as XRD (X-ray diffraction), may be used to measure the strain inside the battery rather than following changes in cell volume outside. Both integrating the FBG sensors inside the battery anode and attaching them to the surface of the Li-ion battery cell allow for the monitoring of strain evolution during the process of charging and discharging. A unique structure is also suggested to improve the sensitivity of the FBG sensors.

Operando through-thickness measurements within a large-scale commercial Li-ion pouch cell are performed in a novel manner using a high-energy XRD approach. Without embedding any intrusive sensors that change battery behavior, the method, which has an in-plane spatial resolution of less than a millimeter, at the same time affects the regional temperature, the local SoC of the two electrodes, and the local in-plane elastic strain in the current collectors. A revolutionary method presented thus allows it possible to separate the mechanical strain and thermal strain that is created during the discharge and charge cycling of the pouch cell, enabling local temperature measurement inside the battery [35].

The SoC parameter is important since it displays the performance of the battery both now and during the course of its remaining life [36]. The longevity and energy transmission or reception capacity of the battery, however, are significantly influenced by SoH [37]. However, direct observation of SoC or SoH is impossible because of the electrochemical processes and non-linear, time-varying characteristics. To estimate SoC/SoH, a variety of models and approaches are utilized along with information about the physical properties of batteries. Numerous estimation techniques have been created over time, with the electrochemical impedance spectroscope (EIS) being a widely used technique for understanding electrochemical processes that are directly associated with battery impedance [38]. It has been used to create various equivalent circuit models (ECMs) that are also used to compute the SoC/SoH of batteries and support the design of adaptive filter algorithms and non-linear observers, such as various Kalman Filter implementations. Machine learning algorithms are utilized to reliably estimate the SoC/SoH of batteries and even assess SoC/SoH variability between cells in packs of batteries due to their powerful data processing and nonlinear fitting capabilities [39–41]. These include scanning transmission electron microscopy (STEM) [42] and electron microscopy (EM) [43] are used for determining the SoC/SoH of batteries by defining the intricate growth of the solid electrolyte interface (SEI) successively and the lithium electrodeposition at the atomic scale in a destructive manner.

Acoustic sensing and OFS is a more recent innovations in battery sensing methods. It can be incorporated inside the battery or attached to the surface and uses computational methods to monitor temperature, strain, and other variables in real-time and determine SoC/SoH [44,45]. Accurate sensing with fine temporal and spatial resolution is required for an advanced and intelligent battery to ensure safe and dependable operation, calculate and forecast the real-time states, and provide a basis for temperature management, management of power, as well as battery life monitoring [46].

3. Advanced Battery Management Approaches for the Sustainable Use of Rechargeable Batteries

The fast adoption of energy from renewable sources and electric automobiles has been facilitated by the need to minimize pollution and dependence on nonrenewable resources [51]. Since batteries are the primary energy storage device for sustainable energy and electric automobiles, they are essential. LIBs are particularly intriguing due to their remarkable performance and rapidly declining price. However, LIBs are frequently used in harsh locations and are subjected to a range of abusive circumstances. The battery's lifespan can be shortened by factors such as overloading, external heat transfer, excessively quick charging, internal/external short circuits, and anomalous temperature rises that could lead to the production of gases or even thermal overrun, the process of combustion, and explosion. Batteries must therefore be handled carefully to ensure their safety and increase their useful life. A BMS is necessary to ensure that battery performance meets the necessities of the automobile for the duration of the battery's life expectancy in addition to monitoring different battery conditions [52].

The four main generations of battery management technologies are "zero or no management," "basic management," "advanced management," and “next generation management” as presented in Figure 3 [53]. The "zero management" approach, which merely regulates charge/discharge by keeping an eye on the terminal voltage of the battery, is only appropriate for older lead-acid batteries with potent anti-abuse features. This generation of batteries underutilizes battery energy, has ineffective control, and necessitates time-consuming maintenance. The "basic management" approach has not greatly improved over the "zero management" system.

The primary goal of the "basic management" system is to enhance the detecting circuit to ensure measurement accuracy and reliability. By continually monitoring external characteristics (such as electrical current, voltage, or temperature) from every single cell in a battery pack online, it may be possible to successfully prevent over-charging and over-discharging. However, it does not offer online monitoring of one's inner states, and it is otherwise relatively simple with very few if any, algorithms. As a result, the workload and complexity of battery care are not reduced because of a lack of understanding of the interior states of batteries. Data and intelligence are the defining characteristics of the next generation of management, which will act as the crucial link between EVs and the energy society, which is made up of many EVs, charging stations, and power plants [54]. More attention is being paid to managing the entire battery lifecycle, from production to recycling, in this generation of battery management.Battery modules require improved management due to the growing quantity of onboard batteries. Advanced management systems come in both centralized and decentralized configurations. The advanced management system, which also prioritizes improving the performance of batteries and the user's experience while driving, enables monitoring of battery system dynamics. There is still significant opportunity for advancement, even though advanced management represents cutting-edge technology in battery management today. Batteries throughout the entire energy society, in addition to the numerous batteries already placed in cars, are the management objects of "next-generation management" systems. The battery system, motor system, and other systems all have different performance needs that must be met by electric automobiles. Figure 4 illustrates the requirement inheritance path for EVs and the performance goals for battery management.

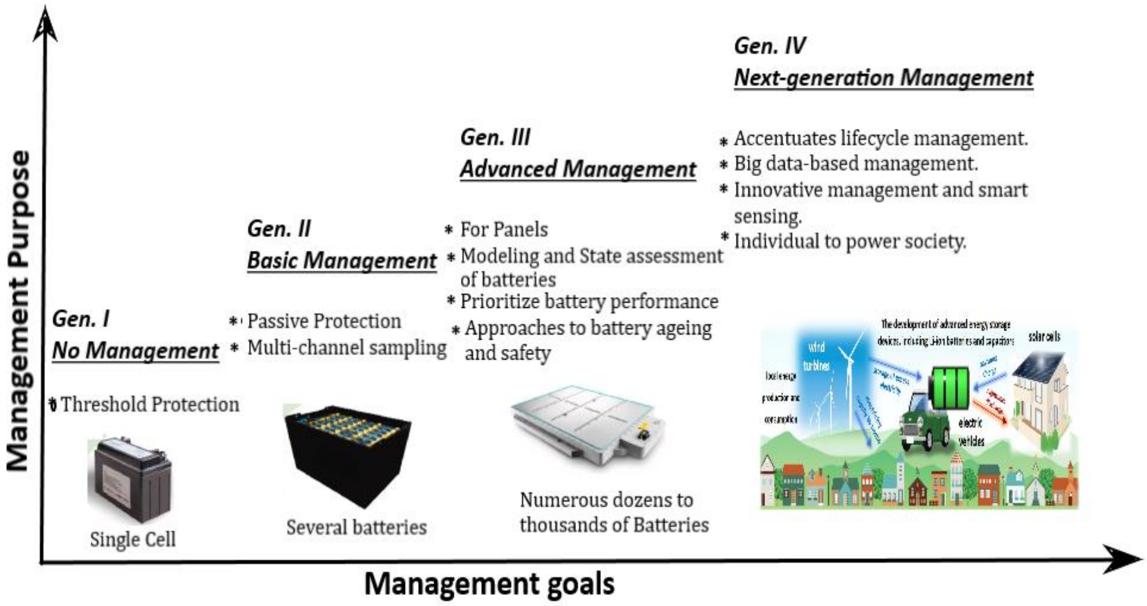

Figure 3. Technology development in battery management.

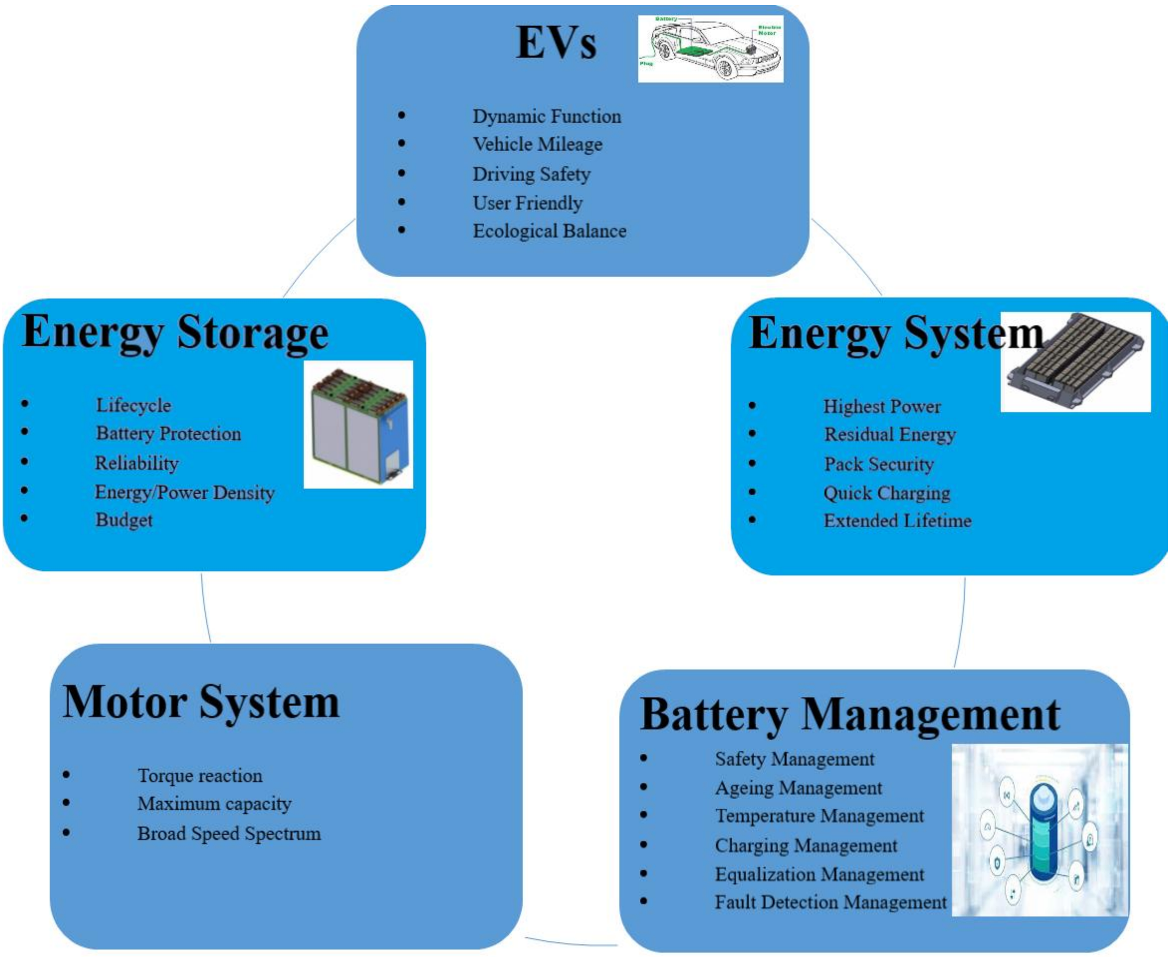

Figure 4. Performance goals for battery management and EVs.

A complete BMS must manage the many influences of operating circumstances, exterior environment, and ongoing issues. Because of this, the battery system needs advanced management techniques to operate safely and effectively. The BMS consists of fault detection, charging/discharging management, equalization management, safety/ageing management, thermal management, and administration of the system. Improved heating, electrical power, ageing, and security performance of the battery system are its primary goals.

3.1 *Thermal Management*

Battery systems must function within a certain temperature range to deliver optimal performance. Both too-low and excessively high temperatures will impair battery performance and result in permanent harm. To achieve the intended battery performance, the battery temperature is controlled by BTMS to a desirable level. This involves heating batteries that are too cold and cooling batteries that are too hot. If a thermal discrepancy occurs, BTMS will also rebalance the distribution of pack temperatures.

3.2 *Charging/Discharging Management*

A crucial barrier to the paradigm change from fossil fuel-powered vehicles to electric vehicles is the charging period of LIBs. Simply speeding up the charging process could result in substantial safety risks, early battery ageing, and significant energy loss. Of their electrochemical and structural characteristics, internal dynamic states, and environmental factors, LIBs have specific charging rate restrictions [55,56]. Security, time spent charging, charge-induced health deterioration, and energy consumption are all factors to be taken into account when charging batteries. These components might interact and collide while a battery is in use.

3.3 *Equalization Management*

The quality characteristics of each cell will alter after several cycles as a result of the dissimilar temperature distribution throughout the pack of batteries, as well as the varied Coulomb efficiencies and self-discharge rates of each cell. Poor performance, a smaller overall capacity, a shorter life expectancy, and even safety issues will be the result of this. Research on LIBs' equalization management is crucial to minimizing performance differences amongst the battery pack's cells [57]. Approaches for equalization can be founded on voltage [58], SoC [59], ability [60], or a mix of these [61–63]. The goal of voltage-based approaches is to guarantee that, within a particular range, the voltage remains constant across all of the individual cells. Due to the straightforward control algorithm and direct voltage measurement, this method is frequently employed in practical applications. A single voltage aim, however, places a cap on the efficiency of equalization.

3.4 *Safety and Aging Management*

Battery ageing management generally aims to increase battery life, whereas safety management guards against hazards including exploitation, explosion, fire, leaking, and others. Utilizing cutting-edge separators, which include inorganic ceramic fibre separators [64], inorganic composite separators supported by paper sheets [65], and enhanced polyimide nanofiber separators [66], can enhance the hydrophilicity and thermal stability of separators. Cathode materials' safety can be improved by using temperature-sensitive electrodes [67,68]. Both the addition of a flame retardant and an additive for overcharge prevention could increase the safety of electrolytes [69,70]. Excessive internal pressure in cells is avoided using explosion-proof valves. Mechanical safety is critical for power storage units like batteries. High-strength materials are used inside battery systems along with sealing devices to protect batteries against penetration and water intrusion, respectively. To avoid battery module dislocation and component fatigue failure, fixation, and damping designs might be used. To increase collision protection, components' bearing and structural strengths might be increased.

To achieve safety management, which is based on temperature safety and high-voltage safety, a system safety-related design is required. This design can be divided into four categories, as shown in Figure 5: cell safety design, structural safety design, electrical safety design, and temperature safety design.

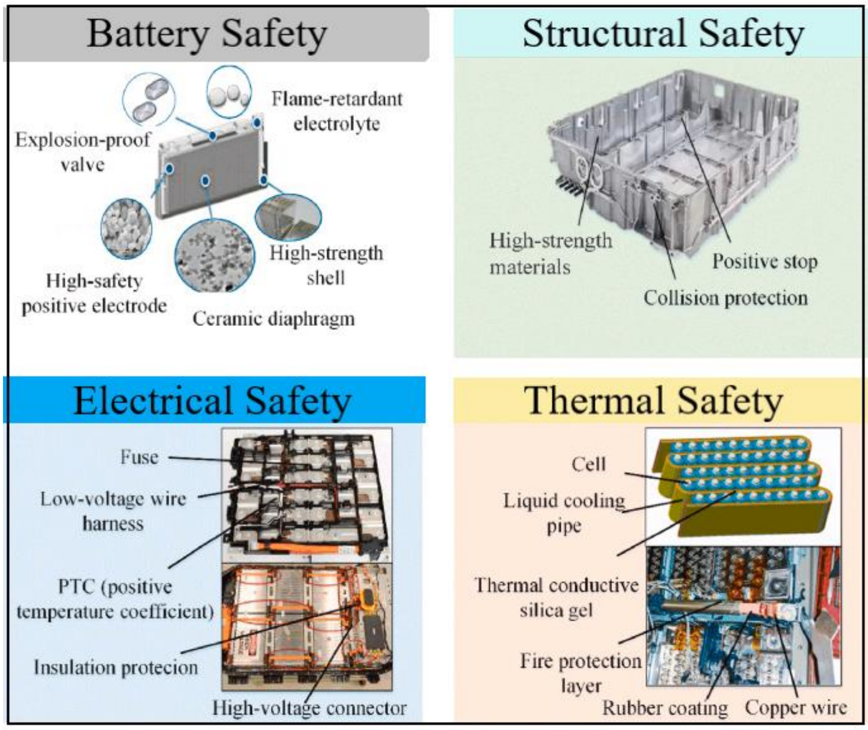

Figure 5. Systems for traction batteries are designed with safety in mind.

3.5 *Fault Detection*

In addition to its safety design, the battery system's safety management system ensures safe and efficient functioning. As a result, fault detection is crucial to enhancing the security and dependability of a battery system. Conventional detection methods use a simple majority voting system for decision-making, hardware redundancy data, and measurements of the same data across many hardware components [71]. These approaches may have drawbacks, including rising expenses, size, volume, and consumption of electricity as well as diminished reliability [72].

When lithium-ion batteries are operating, fault detection technologies can find and assess progressive defects as well as anticipate and recognize unexpected faults [73]. Based on exterior parameters during battery operation, a realistic defect detection approach can assess the battery's health. This benefits battery utilization analysis, battery life extension, and battery maintenance cost reduction. Appropriate fault detection techniques should be used to limit the likelihood of safety issues and assure the effective usage of batteries in light of the complex reaction mechanisms and hazy working circumstances of lithium-ion batteries [74]. Four different groups can be used to categorize fault detection techniques [75].

3.5.1. Technique Based on Statistical Analysis

The approach to statistical analysis is a mathematical technique for drawing inferences from a variety of facts and information using mathematical statistics. Numerous sensors in the battery system gather data on the battery's internal resistance, temperature, voltage, current, and other factors. Utilizing statistical techniques that involve entropy, the distribution of Gaussian, coefficients of correlation, and the maximum probability, the obtained data are directly analyzed. Low computing complexity and great execution efficiency define the statistical analysis-based technique. The voltage curve coefficient of correlation suggested in the article serves as the foundation for the short-circuit fault detection approach [76,77].

3.5.2. Technique Based on Analytical Models

Developing an accurate battery model is the first step in the analytic model-based technique of the battery. Then, to ascertain whether the system is flawed, the model is used to retrieve the parameters conveying fault information. Electrochemical designs, circuit equivalent models, fractional order models, as well as a variety of coupled models are some of the models that can be employed in the current research. The side reaction equations for battery ageing can be used with the electrochemical models to further explore the ageing mechanism of the battery. These models can also reflect changes in many parameters inside the battery. The electrochemical models with several parameters and established partial differential and algebraic equations, however, are too complex for practical applications in the defect evaluation of Li-ion batteries [78,79].

3.5.3. Technique Based on Signal Processing

For detecting faults, the raw signal must be processed. The signal processing-based technique for detecting basic target signals can be regarded as defining a threshold value; if the specified target signal reaches this threshold, the battery will be identified as having a problem. When dealing with difficult-to-detect complex targets, the defect may be connected to the resultant signal's phase, amplitude, frequency, etc [80].

3.5.4. Technique Based on Knowledge

In the early stages of battery defect detection, the knowledge-based technique has found wide applicability. For diagnostic purposes employing knowledge of concepts as well as processing techniques, it mostly relies on intuitive analytical techniques including inferential evaluation and logical judgment. This approach is appropriate for nonlinear and complicated systems and does not necessitate a precise mathematical model. However, it necessitates a thorough investigation of the fault procedure and learning about lithium batteries [81].

4. Battery Sensing Approaches

The typical measurement data for battery sensors—voltage, current, and temperature—are still under development and are more closely related to the battery's electrical and thermal data. A more thorough knowledge of the battery will be possible with the addition of some smart measurement data on the electrochemical, mechanical, acoustical, and optical performances of the battery. A further recent advancement in battery sensing techniques is acoustic and optical sensing, which can be integrated into the battery or connected to the surface to continuously record temperature, strain, and other characteristics and, using algorithms, estimate SoC/SoH [44,45]. One of the most crucial stages that must be maintained to enhance performance and lengthen the lifespan of batteries is the state of charge (SoC), which represents the capacity of the battery [82]. Systems of today frequently draw their estimators from measurements of voltage, current, and temperature, which might result in incorrect value estimates while the system is operating. Recent years have seen a huge increase in the use of mechanically based measures to close data gaps, supplement conventional measurements, and offer more precise data regarding the internal condition of lithium-ion batteries [83]. Accurate sensing with fine temporal and spatial resolution is essential for an effective and advanced battery to ensure safe and dependable operation, determine and anticipate the real-time states, and provide a basis for controlling the temperature, energy management, as well as battery life management, emphasized in [46]. A high-safety charging strategy is required due to the increasing demand for high energy storage density, which is pushing LIBs to larger design sizes. This increased demand for high energy storage density places an ever-increasing demand on accurate management of battery operating conditions. Emerged BMSs have improved recently, but they still rely on complicated algorithms, and new hardware units, like implanted sensors, need to be developed in order to learn about the battery's internal state. The efficiency of management will be further improved by having access to the operating batteries' internal data, which will substantially increase the accuracy of status estimation [84].

4.1 *Electrochemical Sensing*

Electrochemical sensing is used to examine the electrode electrochemical method, which is visible in battery impedance spectroscopy. To characterize and model batteries, impedance spectroscopy has been utilized successfully in the laboratory. Direct onboard evaluations of battery life impedance have also been proven to be accurate. Two methodologies for online battery impedance measurements seem promising. One approach requires the use of an AC signal generator integrated into the vehicle that can supply the battery with power at a specific frequency [85]. Therefore, the battery impedance at different frequencies may be calculated using the load current and measured voltage. The alternative method is more flexible, and signal processing methods like the Fourier transformation and the wavelet transformation can quickly gather the battery impedance during the running current or step over a wide frequency range [86].

Rechargeable battery management is facilitated by AC impedance spectra. An onboard impedance measurement system with an affordable price and low level of complexity must be realized by the management based on the AC impedance. Wang et al. introduced a novel impedance measurement system with distributed sample units and a high-power dual active bridge (DAB) converter. The DAB converter is configured to provide the AC disturbance to measure the battery impedance almost consistently. To determine a module's impedance (shown in Figure 6), distributed signal sampling devices concurrently monitor the voltage and current of all the battery cells connected in series with the module The technology's distinctiveness is reflected in how easily it can be included in a bidirectional onboard charger and how well it works with the battery management system, which reduces both expenses and complexity [87].

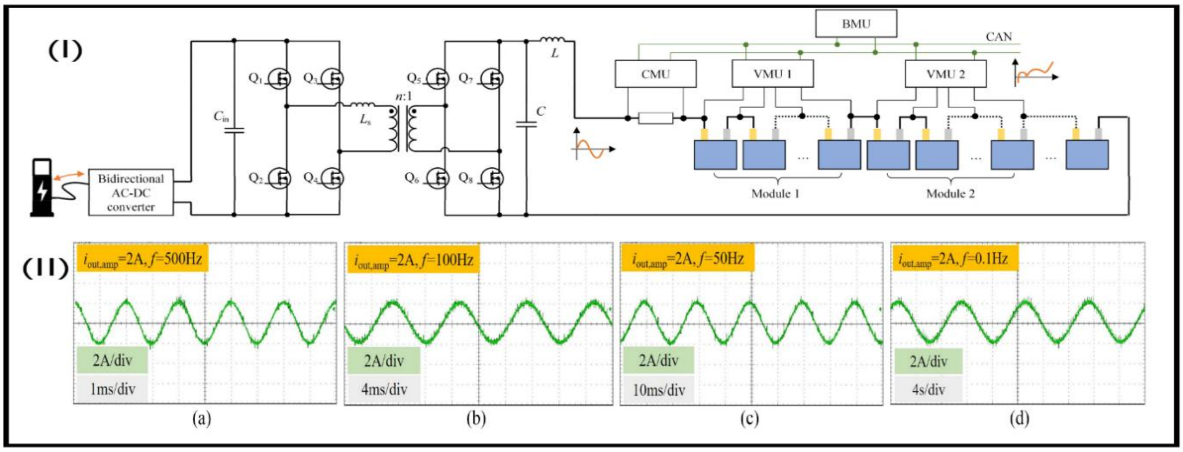

Figure 6. (I) Battery impedance measurement system implementation. (II)The DAB converter generates the following output current waveforms at various frequencies: (a) 500 hertz, (b) 100 hertz, (c) 50 hertz, and (d) 0.1 hertz [87].

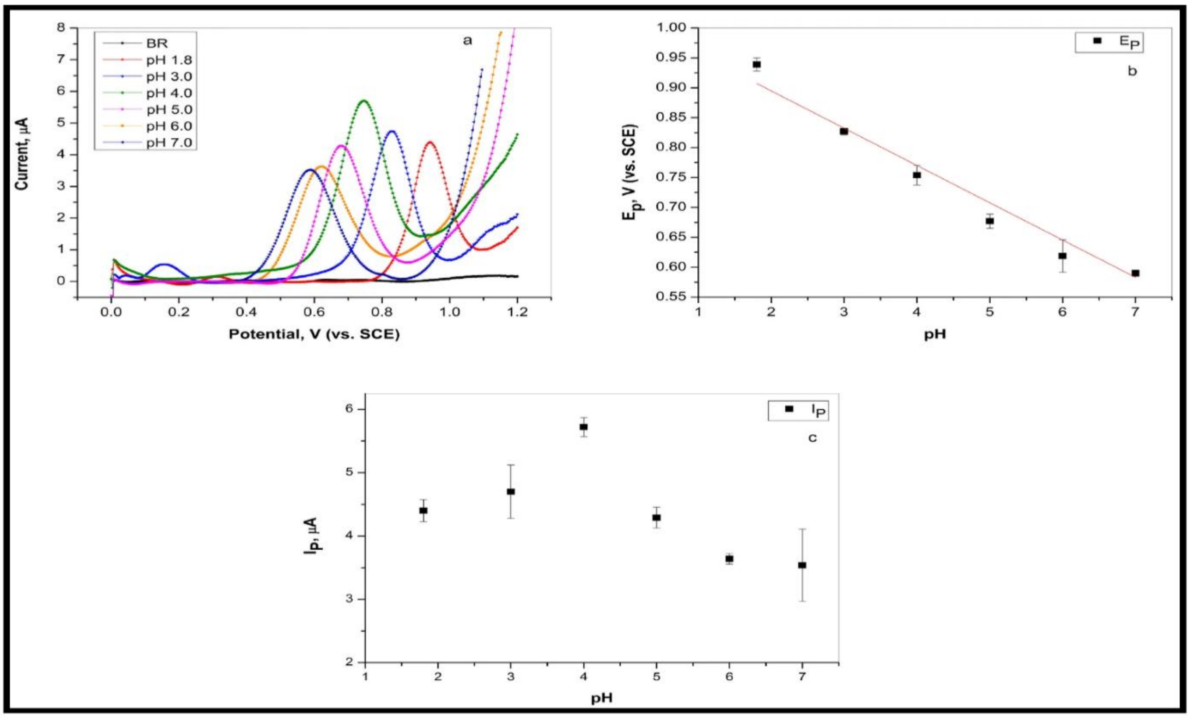

Figure 7. With a scan rate of 50.0 mV/s, differential pulse voltage measurement curves of 100.0 M L-tryptophan on a graphite electrode in a pH-variable Britton-Robinson buffer solution were recorded [88].

An electrochemical sensor that could recognize the target analytic was low-cost and non-toxic and was designed to help reduce electronic waste as demonstrated by Tasic et al. According to this, an electrochemical sensor for measuring L-tryptophan in the Britton-Robinson buffer mixture was developed using a graphite rod from zinc-carbon batteries. Both the peak potential and the intensity of the L-tryptophan oxidation peak were influenced by the pH of the Britton-Robinson buffer. The peak potential value fell when the pH was between 4.0 and 6.0, demonstrating that protons were also engaged in the process of redox (see Figure 7). The strength of the current response peaked at pH 4.0 [88]. According to research by Narayana et al., Li_2TiO_3-multiwalled carbon nanotube nanocomposite (LTO-MWCNT) made utilizing a one-step hydrothermal technique is being evaluated as an electrochemical detector for medicinal product formulations (see Figure 8). Concerning the dopamine injection formulation, the newly built LTO-MWCNT/GC detector displays 98% satisfactory recoveries and is accurate and precise. The LTO-MWCNT/GC sensor has a lot of promise for use in assessing DA and medication formulations, according to these findings [89].

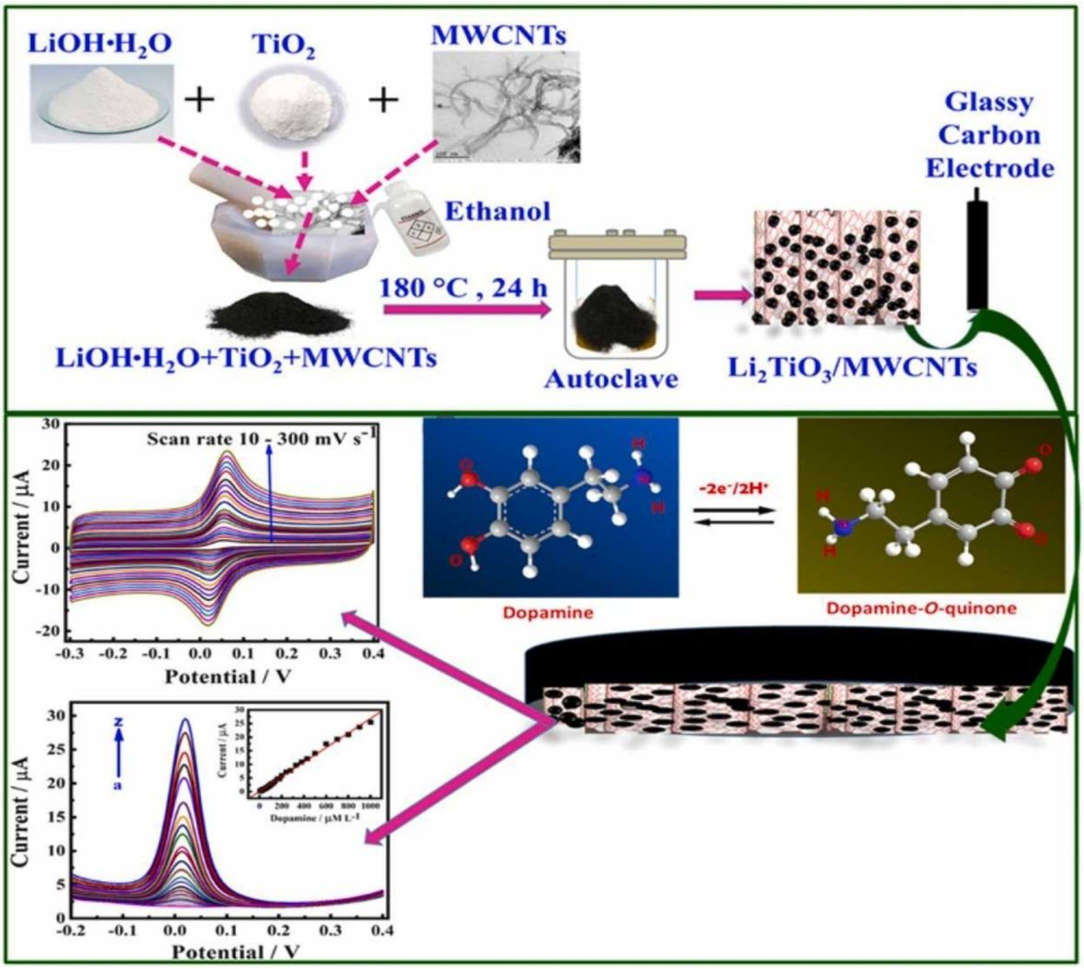

Figure 8. Dopamine measurement using Li_2TiO_3-MWCNT nanocomposite electrodes in an electrochemical sensor platform [89].

4.2 *Mechanical Sensing*

When a battery is charged or discharged, the behaviors of the lithium ions during insertion and ejection resemble "breathing," changing the tension on the battery and resulting in deformation. For battery applications, mechanical detection is just as important as electrical and thermal detection, but it can be difficult to determine battery stress or distortion, especially for outboard purposes. A stress sensor as well as a strain gauge can currently be mounted on a battery to measure its stress. The battery's SoC and SoH may then be determined, as well as the irreversible volume growth caused by SEI development, can be identified using mechanical data [90,91].

Operando pressure measurements were used by Louli et al. to give a simple approach for detecting the formation of the solid electrolyte interphase (shown in Figure 9). To produce cells with better energy densities, silicon-containing negatively charged Li-ion batteries are now being released on the market. The large volume increase of silicon, however, causes these batteries to exhibit rapid SEI development and shortened lifespan. They provide an example of how to rank the performance of the cells by assessing the pace of SEI generation and tracking operando pressure in silicon-containing cells [49]. Given the numerous cells that make up the current automotive battery packages (some hundreds in the case of strong-capacity cells, a few hundred for solutions based on small cylindrical cells, like in Tesla vehicles), the integration of mechanical sensors in the individual cells, even in the case of inexpensive strain gauges, still appears prohibitive. On the other hand, using mechanical sensors for in-operando investigations of Li-ion cells is a very potent way to enhance battery modeling software and the BMS approaches that go along with it [92].

A rectangular rosette gauge for strain and two piezoelectric transducers have been used to monitor the normal operation of a 18650 lithium-ion cell. Information regarding the mechanism of cell deformation and the structure of the electrodes during cycling is provided by sensors used for mechanical measurements. Three different mechanical processes were identified by the strain gauge output. As a result of the extraction of lithium ions from the graphite negative electrode, an isotropic cylindrical shrinkage is the primary deformation pattern during the galvanostatic discharge process. When the state of charge drops below 40 in cyclic voltammetry mode for close to zero-rate discharge, the deformation pattern transforms into spherical growth [93].

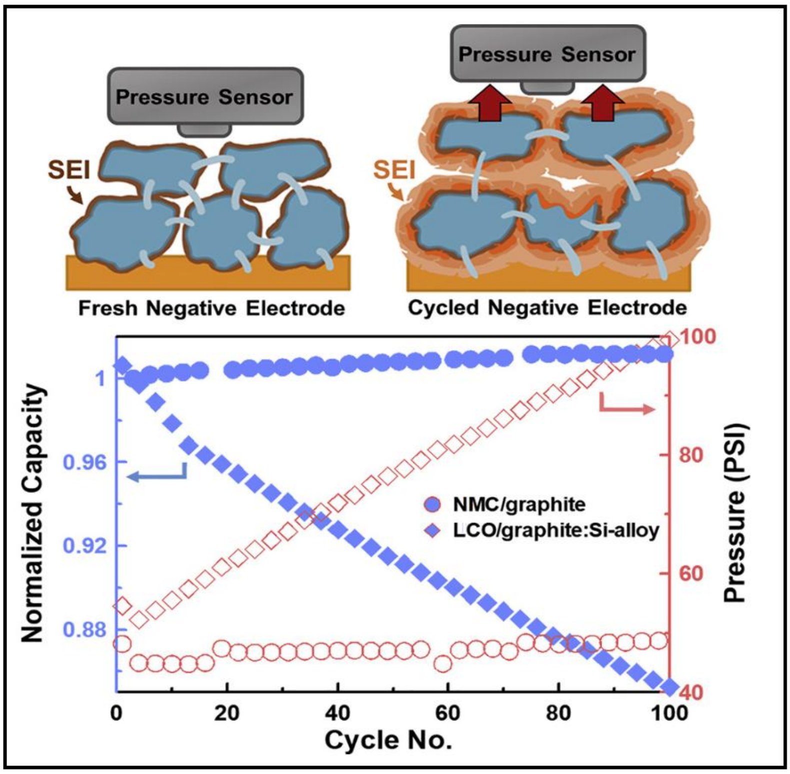

Figure 9. Representation of Operando Pressure Measurements [49].

4.3 *Acoustic Sensing*

When a battery cycles, its volume expands and contracts, changing both its acoustic impedance and its volume. Acoustic sensing is a special method for battery sensing and detection that takes advantage of this phenomenon. Ultrasonic diagnostics, one of the non-destructive characterization techniques for materials, has had some early success when it comes to internal detection of gas, electrical abuse monitoring [94], and state estimation. When evaluated after the transmitting device generates the pulse signal, the peak height and delay time of the received wave show significant relationships with the SoC of the battery [95] as well as electrochemical charge/discharge cycling and ageing [96]. The acoustical sensing generator and receiver are still in the laboratory stage, similar to the aforementioned stress sensing. Acoustic sensing is subdivided into two: passive and active acoustic sensing (see Figure 10).

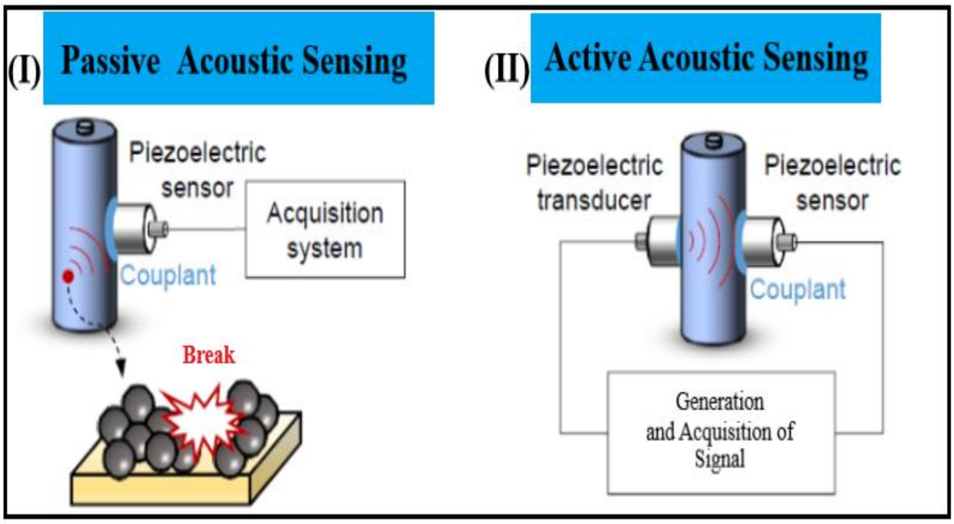

Figure 10. Schematic representation of passive and active acoustic sensing.

4.3.1. Passive Acoustic Sensing

Along with the degrading mechanisms brought on by electrolytes, the mechanical development of electrodes frequently leads to fracture occurrences and an associated release of electrical power. Accordingly, as shown in Figure 11, these events result in the emission of acoustic waves that depend on the inherent properties of the material (crystallographic arrangement, size of grains, changes in phase, etc.). These waves also depend on stresses that are created during cycling [97,98]. Thus, acoustic emission (AE) characterization appears well suited for monitoring a material used for electrodes that go through transitions in phase and continuously expand or contract throughout cycling, leading to a variety of fracture forms and locations, as it is a non-destructive and passive technique. The quick detection of degradation (cracks, stress) in the construction of concrete and the development of preventative maintenance through the strain mapping of aeronautical components are two common applications of AE in civil engineering. AE has had a difficult time making a name for itself in the battery industry, even though it was used to study the beta-alumina electrolyte degradation in extreme temperatures of sodium-sulfur batteries in the early 1970s [99]. The work of Ohzuku et al., in which Li/MnO_2 coin cells were implanted with an acoustic transducer connected to the cell shell using silicon grease [97], rekindled interest in it in the 1990s. The authors discovered events that they connected to electrochemical grinding of the electrodes, phase transitions, or gas formation by analyzing the acoustic emission signals produced by the cell during cycling. They also suggested that it would be possible to forecast or forewarn cell failure using such an analytical method. This provided the foundation for more recent AE sensing applications in the realm of batteries, including studies into SEI formation, Li-driven volumetric variations in graphite and silicon substrates, and chemo-mechanical effects in multilayer oxide substrates [100,101]. According to Choe et al., waveform analysis using scanning electron microscope (SEM) data allowed for the identification of two distinct types of AE events in $LiCoO_2$/C cells [102]. These events, which were attributed to SEI development and $LiCoO_2$ fracture, respectively, were revealed over two distinct frequency areas The AE spectra will depend on cell chemistry, as demonstrated by recent research on $LiNiO_2$/Li cells where three different types of acoustic events can be distinguished during cycling [103]. Along with particle fracture, the positive electrode also showed signs of the cathode electrolyte interphase (CEI) growing. Cell voltage guidance, however, was required to identify these occurrences, along with concomitant EIS and SEM data. Therefore, even though the very sensitive approach is rather simple to use, its challenge lies in how difficult it is to connect observable events with their physical basis unless it is supported by other analytical methods.

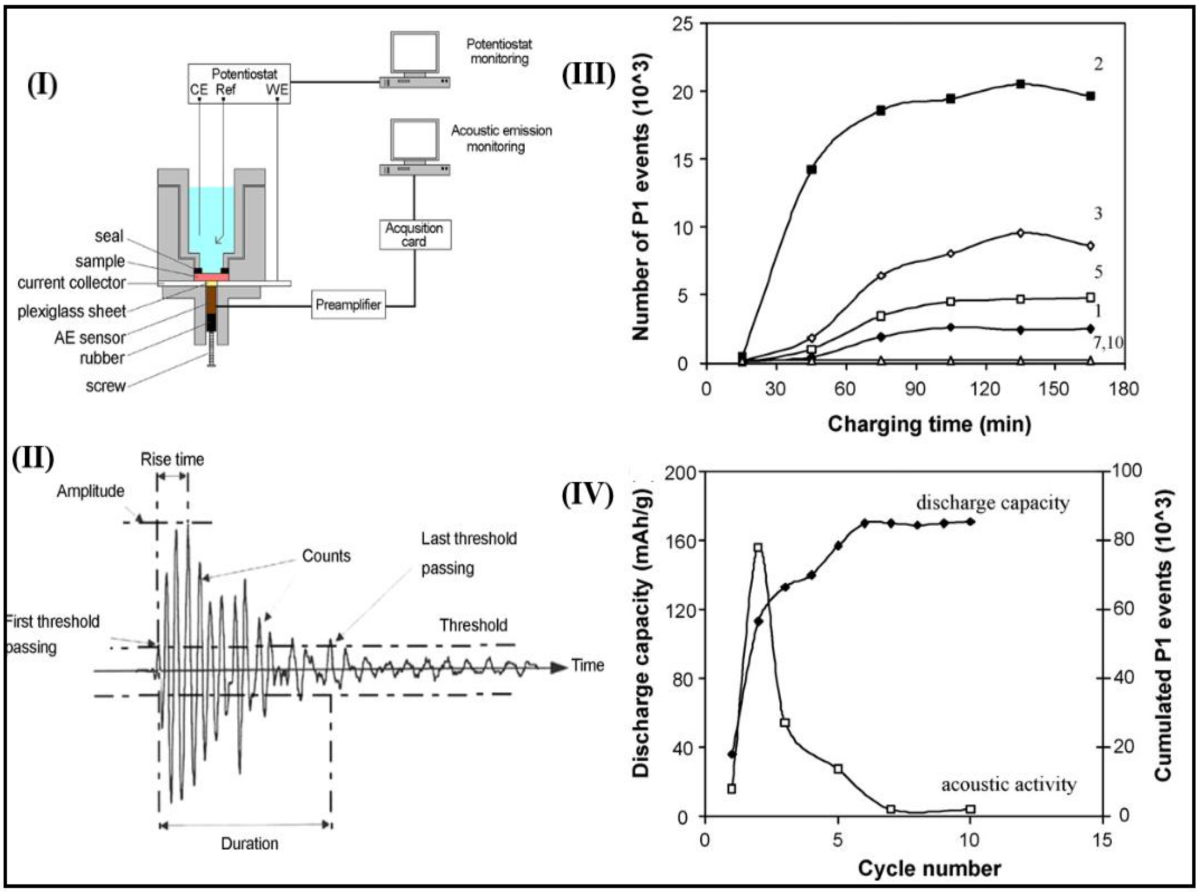

Figure 11. (I) Experimental setup linking AE and electrochemical measurements, (II) Primary auditory properties of a typical waveform signal, (III) Population P1 evolution during charging via cycling on the $LaNi_5$-based electrode, and (IV) Correlation between the $LaNi_5$-based electrode's discharge capacity and cumulated P1 acoustic activity [98].

4.3.2. Active Acoustic Sensing

Acoustic ultrasound characterization is being used in new investigations. It is an active, but non-destructive method that makes use of two piezoelectric transducers [104–107]. One sensor cycles the battery by injecting sound waves at a specific frequency, while the other sensor detects the wave once it has moved through the battery medium. The wave's propagation speed and amplitude retardation are both influenced by the loading process of the electrolyte, residual bubbles of gases, and other properties of the electrodes, separators, and current collector surfaces that it is crossing, among other factors. It is possible to simulate the time-of-flight (ToF) "versus" amplitude spectrum of receiving pulses using elastic wave propagation theory, which is temporally recorded upon cycling, despite the spectra's complexity. It is possible to deduce a connection between the ultrasonic spectrum and SoC from this data. An explicit example is provided by an operand study of commercialized $LiCoO_2$/C pouch cells that were investigated in several SoC employing pulses of 200 kHz. The amplitude along with the ToF of one peak of the rectified incoming pulses showed a linear dependence on the SoC (see Figure 12) [95], allowing models for forecasting the SoH to be developed [108].

By building an ultrasonic imaging apparatus out of two portable ultrasonic sensors placed on each side of a pouch cell while the entire cell is submerged in silicone fluid for ultrasonic coupling, J. Dahn et al. recently showed how to use ultrasound in the field of batteries more simply and effectively [109,110]. By measuring the transmitted wave's amplitude, the authors were able to see how the electrolyte was distributed within the cell as a result of impregnation time and electrolyte concentration because the transmitted signal's attenuation differed significantly between dried, wetted, and gas-containing electrodes. Researchers were also able to spot the first indications of gassing and calculate how many cycles are left before the cell dries up by cycling the Li-ion NMC/C cells with varying temperatures, threshold voltages, or electrolytes. As a result, it presents the opportunity to track cell performance over time and aid with Li-ion pouch cell electrolyte filling using ultrasonic imaging. In LIB production facilities, this might be very helpful for online inspection if there are methods available to control the inclusion of silicone oil.

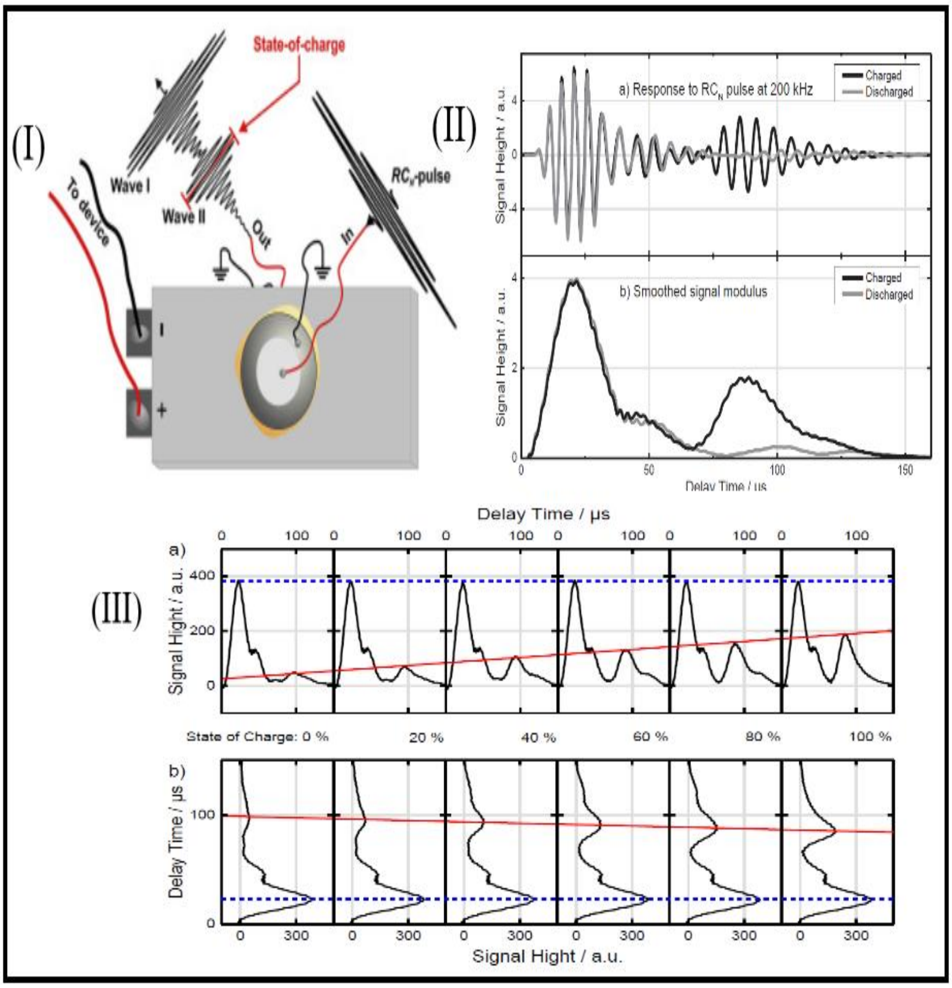

Figure 12. (I) Ultrasonic pulsed excitation for state-of-charge estimation, (II) Transmission of RC_N-pulses across a completely charged and fully depleted lithium-ion battery pouch cell, (III) Transmission of RC_N-pulse signals with a smoothed modulus through a lithium-ion battery pouch cell [95].

The sensors that have been previously addressed (temperature, strain gauge, electrochemical, as well as acoustic) provide several benefits and give the ability to obtain critical metrics for monitoring the degeneration of commercial devices under simulated working conditions. With Exceptustic technologies, the majority of these sensing techniques can scarcely access several metrics with any degree of accuracy. Although acoustics is excellent at showing the results of mechanical effects, it has trouble identifying the precise causes. They also do not give users immediate access to crucial temperature or thermodynamics observables. The advent of optical sensing, on the other hand, makes it possible to access related physical, thermal, and chemical characteristics that are crucial for predicting cell death or preventing thermal runaway as well as tracking the dynamic chemistry of parasitic events.

4.4 *Optical Sensing*

4.4.1. Sensor with an Optical Fibre Bragg Grating

The evolution of communications technologies based on optical fibres and optoelectronic devices has helped the development of optical sensors for several applications in the engineering and healthcare sectors. The variety of optical sensing techniques is based on the many physical processes whereby light interacts with materials through scattering, diffraction, or absorption. These interactions for fibres may occur along the whole length of the fibre or may be selectively localized to provide distributed or quasi-distributed sensors. Single-mode optical fibres (SMF) employed in optical fibre bragg grating (FBG) detectors, for instance, have a periodic fluctuation in the refractive index engraved across a small distance [111].

A well-known technology utilized in many applications, such as building, construction, and assembly sectors for structural health monitoring, is the Bragg grating area of SMF-FBG sensors, which functions as a reflector for a certain wavelength λB. They work by connecting the local temperature (T), pressure (P), and strain (ε) of the environment to the wavelength dependence of the signal (λB) [35]. They are capable of multiplexed, multi-parameter sensing, are electromagnetic interference-resistant, environmentally benign, insulating against electricity, compact, and have a small form factor [111]. These benefits have led to the employment of SMF-FBG sensors in fuel-cell battery stacks for temperature and control of water by simultaneously monitoring local temperature and humidity (with a polymer layer) during transient operating conditions [112].

SMF-FBG sensors have also been used in the production of batteries due to the creative work of PARC (a Xerox company), Pinto's group, and others [113–116]. Under actual operating conditions, FBGs were shown to be effective at capturing accurate cell temperature images of Li-ion pouch cells and cylindrical cells [117–120]. As a result, it was possible to examine how overcharging or an external short-circuit affected heating inside the cell core and gain access to the temperature gradient that was electrochemically created there. To decouple ε and T, two sensors can be used, including two FBGs or one FBG plus one Fabry-Perot sensing device [121,122]. In addition to monitoring the temperature with exceptional sensitivity and spatial resolution, FBGs are sensitive to strain (ε). In their foundational work, PARC showed how pairs of FBGs can be smartly configured to monitor strain and temperature in sizable-format lithium-ion pouch cells for electric automobile uses [22,119–122]. In many different operational and safety-critical circumstances, this approach is the most effective way to monitor these variables. Based on the precision of the strain measured by FBGs, they were able to predict the capacity up to 10 cycles with a 2% error in advance, allowing them to estimate the SoC of the pouch cells under different temperature settings and dynamic cycling with an error of less than 2.5%. As a result, it implies that cell capacity can be inferred via strain measurement. Further integrating an FBG sensor into the graphite electrode of a liquid pouch cell and surreptitiously converting strain into stress to monitor its fluctuations are also possible, as demonstrated by PARC. Currently, this method is being successfully applied to batteries made from solid-state materials, demonstrating the viability of tracking stress evolutions at interfaces as well as within solid composite electrodes, and providing recommendations for electrode architectures and cell assembly topologies in highly awaited solid-state storage devices [123].

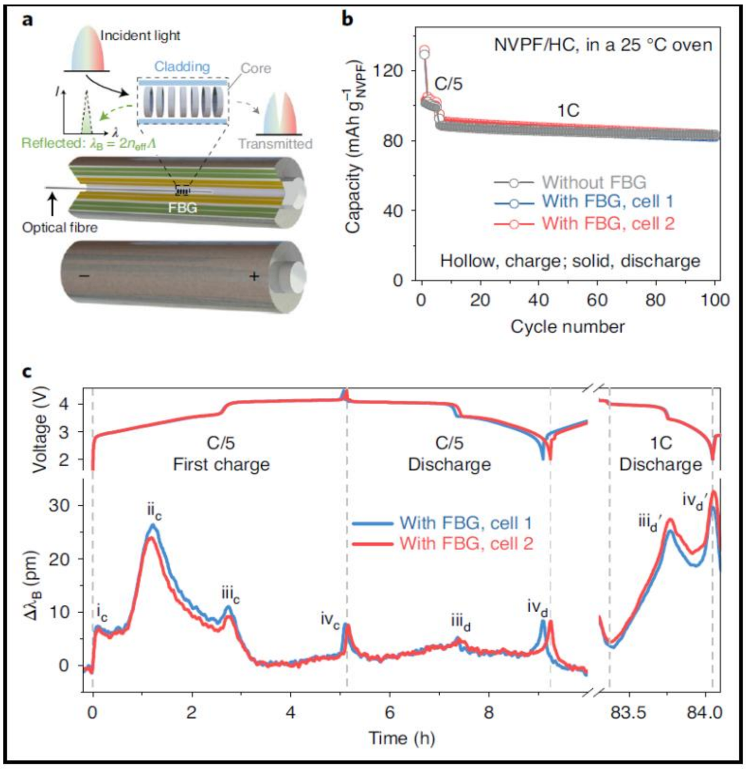

Figure 13. Battery-internal optical fibre sensing concept [46].

Despite the above-mentioned insights from SMF-FBGs, which are associated observables with battery SoC or SoH, the relationship between the measurements and the fundamental chemistry was not founded. In a recent study, Huang et al. combined an SMF-FBG with a second FBG that was designed in a microstructured optical fibre (MOF-FBG), giving a significant response to pressure from hydraulics due to the design of its air-hole pattern. The gap between the two FBGs was only partially filled by this study. As a result, the cell can precisely decouple its internal conditions of pressure and temperature throughout cycling. They used 18650 commercialized Na-ion cells, which depend on the NVPF/C cell chemistry, to show that it is possible to trace chemical events, such as the development of SEI and the formation of parasitic chemical processes. We can also indirectly monitor and analyze the flow of heat produced by the cells during various applications owing to a novel operando optical calorimetry technique developed employing a thermal model and many FBG sensors (Figure 13) [46]. It makes it possible to obtain the contributions to heat capacity and, as a result, fully parameterize battery thermal models, unlike isothermal calorimetry [124]. These results allow for the monitoring of interfacial processes and offer a scalable way for evaluating the function of electrolyte compounds during the process of SEI/CEI production, as most recently shown by the discovery of a highly efficient electrolyte formulation for Na-ion cells [125]. Additionally, to design battery temperature management systems, it is essential to comprehend the thermodynamic characteristics of the cell as determined by this method [126].

4.4.2. Evanescent Wave Sensor Made of Fibre Optics

We must first overcome the scenario where light is blocked inside the fibre core, as previously mentioned relative intensity (RI), to gather detailed chemical data regarding the materials used for electrodes, Li inventory, or electrolyte parameters like the refractive index. An optical sensing technology that relies on the interaction of the evanescent field with the surfaces at the fiber-to-medium interface (FOEWS) is used, for instance, by an optical fibre evanescent wave sensor to quantify refractive index variations. To enable this, the optical fiber's design must be changed so that light moving along its axis can partially elude the core and reach the contact between the fibre and the surroundings. Evanescent waves are generated when the fibre cladding is partially or entirely removed. This can be done by etching [127], polishing, or even simply writing FBGs on the cladding. These waves can travel up to a hundred nanometers through the external medium [128]. Another technique entailed either extending the FBGs' grating period (from 500 nanometers to a few hundred micrometers) or sloping the grating plane, which led to the creation of two additional kinds of sensors known as long-period grating (LPG) as well as tilted fibre bragg grating (TFBG) sensors, respectively [127,128]. LPG and TFBG are useful for practical gas/liquid detection, (bio-)chemical sensing, and electrochemistry applications like supercapacitors because they are responsive to the related refractive index when the light from these devices' cladding modes penetrates the surrounding fibre environment [129,130] (see Figure 14).

Plasmonic sensors, which in this regard can be viewed as fibre optics coated by an extremely thin metal coating that induces a resonance called surface plasmon (SPR), are by nature hypersensitive to the ambient atmosphere's relative intensity (RI) [131]. The scientific community has become interested in Surface Plasmon (SP) based biosensors recently due to their numerous applications and outstanding performance. These sensors have emerged as attractive options for biosensing applications by utilizing surface plasmon resonance (SPR) and SP propagation at metal-dielectric principles [132]. To give improved RI sensitivity than bare TFBGs, a metal coating (often Au, Ag, etc.) is applied to a fibre carrying a TFBG. This is one possible implementation of an SPR sensor. Guo and Albert et al. (2018) demonstrated that they used a TFBG-SPR sensor to monitor the SoC of a supercapacitor since the electrolyte content in a supercapacitor varies with SoC (anions adsorb at one of the electrodes, whereas cations adsorb at the second) [45].

The precise features of the electrolytes being evaluated, changes brought on by a particular electrolyte's deterioration, or variations in the amount of salt or solvent content within the electrolyte are all still unknown, although the potential advantage of RI. Unfortunately, the cell's dynamic chemistry is still a mystery. Do optical sensors have the ability to detect this chemistry? Given that other spectroscopic method, including Raman, phosphorescence, and IR spectroscopy spectroscopies, also make use of evanescent waves, this may be one of the most promising features of such sensors [133,134]. A step in this direction was taken when it was revealed that the lithiation of graphite electrode is related to a transmittance in the NIR (near-infrared) region (700-900 nm) within the silicon dioxide fibre transmittance zone (0-3m). Thus, the variations in graphite's optical properties can be identified by expanding the FOEWS from RI to spectroscopic measurements. Using these

FOEWS, it is possible to calculate the SoH and measure the SoC of graphite by keeping an eye on the inventory loss of Li during cycling. In one experiment, while the cells (each with a distinctive composition of electrolyte) underwent electrochemical cycling, $Te_2As_3Se_5$ glass fibres were placed into the inner holes of 18650 Na-ion batteries and connected to a NIR electromagnetic signal transmitter and receiver [135]. In one experiment, while the cells (each with a distinctive composition by looking at the obtained spectra from the creation cycle and prolonged cycling, it is possible to quantify Na-alkyl carbonates with Na-methoxy species. This is made possible by the appearance of additional infrared radiation bands in devices using DMC-based electrolytes. By using infrared absorption spectroscopy, it is possible to characterize chemical species as they emerge during battery construction and cycling, extending battery life and increasing the likelihood of sustainability.

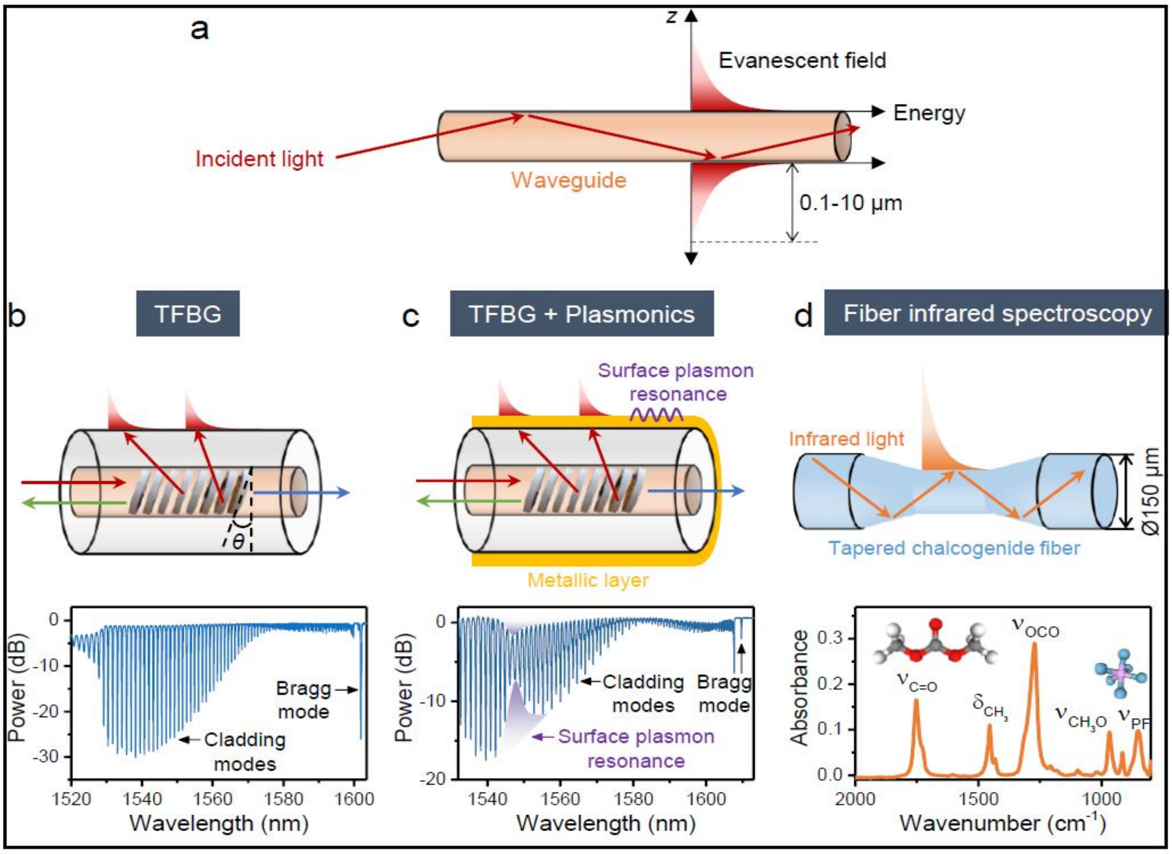

Figure 14. Representation of evanescent waves for optical sensing: (a) the underlying FOEWS principle, as well as the numerous sensors that rely on it, (b) accompanied by a standard resonance spectrum, (c) an adapted version of where a thin metallic plasmonic film was placed to activate the surface plasmon resonance, (d) An operando measurement using a tapered chalcogenide fibre and an accompanying infrared absorption spectrum collection [135].

5. Summary and Conclusions

LIBs are widely used due to features such as elevated voltage, prolonged cycling life, and reduced self-discharge. Sensor data provides information on temperature and stress, enabling computer models. A robust battery sensing system is needed. Handling batteries carefully is essential to protect their security and shelf life, and a BMS is needed to ensure battery performance meets the needs of the automobile. Battery sensors can be used to measure the electrical and thermal characteristics of the battery, as well as its electrochemical, mechanical, acoustical, and optical behaviors. Electrochemical sensors can identify an AC signal generator, while mechanical sensors can measure the SoC and SoH of the battery and detect volume expansion caused by SEI growth. Acoustic sensing, ultrasonic diagnostics, and optical sensors are being developed to detect physical-chemical-thermal parameters and link them to SoC, SoH, and SoP, as well as the state of safety of storage devices.

They can be used in both aqueous and non-aqueous environments. A novel approach to understanding a battery's theoretical functionality during real-time use will be provided by fusing the development of these diagnostic tools with cutting-edge BMS strategies. Batteries will become more user-friendly, useful, and less replaceable if they provide correct information and, more critically, information history. This tactic can increase their general adoption in the transportation sector and other industries, some of which may be early converts due to their more stringent operating requirements and higher cost endurance than electric automobiles (such as aviation and military). The monitoring of battery parameters at the component level, including temperature (T), pressure (P), strain (ε), the liquid electrolyte layer (RI and parasitic chemical species), and the level of the interface, is necessary to increase battery dependability and sustainability, as we have previously stated.

Acknowledgment

The authors would like to thank Photonics Research Laboratory, School of Studies in Electronics & Photonics and Institute of Renewable Energy Technology & Management, Pt. Ravishankar Shukla University, Raipur (C.G.), India for supporting this work.

Conflict of Interest

There is no conflict of interest for this study.

Abbreviations

LIBs	Lithium ion-based batteries
BMS	Battery Management System
SoC	State of charge
SoH	State of health
SEI	Solid electrolyte interphase
IoT	Internet of Things
EVs	Electric vehicles
UBHC	The upper bound of the heating current
QRL	Quality, Reliability, and Life
TC	Thermocouples
RTD	Resistance temperature detectors
XPS	X-ray photoelectron spectroscopy
XRD	X-ray diffraction
SEM	Scanning electron microscope
EIS	Electrochemical impedance spectroscope
ECMs	Equivalent circuit models
STEM	Scanning transmission electron microscopy
OFS	Optical fibre sensor
EIS	Electrochemical Impedance Spectroscopy
DAB	Dual active bridge converter
LTO-MWCNT	Li_2TiO_3-multiwalled carbon nanotube nanocomposite
AE	Acoustic emission
CEI	Cathode electrolyte interphase
FBG	Fibre bragg grating
BTMS	Battery thermal management system
SMF	Single-mode optical fibres
MOF	Microstructured optical fibre
RI	Refractive index
LPG	Long-period grating
TFBG	Tilted fibre bragg grating
SPR	Surface plasmon resonance
FOEW	Fiber optic evanescent wave
NIR	Near-infrared region

Symbol Description Unit

T	Local temperature
P	Pressure
ε	strain
λ_B	Wavelength dependence of the signal

References

[1] Larcher, D.; Tarascon, J.-M. Towards greener and more sustainable batteries for electrical energy storage. *Nat. Chem.* **2014**, *7*, 19–29, https://doi.org/10.1038/nchem.2085.

[2] Wei, Z.; Hu, J.; Li, Y.; He, H.; Li, W.; Sauer, D.U. Hierarchical soft measurement of load current and state of charge for future smart lithium-ion batteries. *Appl. Energy* **2021**, *307*, 118246, https://doi.org/10.1016/j.apenergy.2021.118246.

[3] Wei, Z.; Ruan, H.; Li, Y.; Li, J.; Zhang, C.; He, H. Multistage State of Health Estimation of Lithium-Ion Battery with High Tolerance to Heavily Partial Charging. *IEEE Trans. Power Electron.* **2022**, *37*, 7432–7442, https://doi.org/10.1109/tpel.2022.3144504.

[4] Quilty, C.D.; Wu, D.; Li, W.; Bock, D.C.; Wang, L.; Housel, L.M.; Abraham, A.; Takeuchi, K.J.; Marschilok, A.C.; Takeuchi, E.S. Electron and Ion Transport in Lithium and Lithium-Ion Battery Negative and Positive Composite Electrodes. *Chem. Rev.* **2023**, *123*, 1327–1363, https://doi.org/10.1021/acs.chemrev.2c00214.

[5] Thakur, A.K.; Sathyamurthy, R.; Velraj, R.; Saidur, R.; Pandey, A.; Ma, Z.; Singh, P.; Hazra, S.K.; Sharshir, S.W.; Prabakaran, R.; et al. A state-of-the art review on advancing battery thermal management systems for fast-charging. *Appl. Therm. Eng.* **2023**, *226*, https://doi.org/10.1016/j.applthermaleng.2023.120303.

[6] Khaboshan, H.N.; Jaliliantabar, F.; Abdullah, A.A.; Panchal, S. Improving the cooling performance of cylindrical lithium-ion battery using three passive methods in a battery thermal management system. *Appl. Therm. Eng.* **2023**, *227*, https://doi.org/10.1016/j.applthermaleng.2023.120320.

[7] Li, W.; Xie, Y.; Hu, X.; Tran, M.-K.; Fowler, M.; Panchal, S.; Zheng, J.; Liu, K. An Internal Heating Strategy for Lithium-Ion Batteries Without Lithium Plating Based on Self-Adaptive Alternating Current Pulse. *IEEE Trans. Veh. Technol.* **2022**, *72*, 5809–5823, https://doi.org/10.1109/tvt.2022.3229187.

[8] Zhou, L.; Lai, X.; Li, B.; Yao, Y.; Yuan, M.; Weng, J.; Zheng, Y. State Estimation Models of Lithium-Ion Batteries for Battery Management System: Status, Challenges, and Future Trends. *Batteries* **2023**, *9*, 131, https://doi.org/10.3390/batteries9020131.

[9] Fichtner, M.; Edström, K.; Ayerbe, E.; Berecibar, M.; Bhowmik, A.; Castelli, I.E.; Clark, S.; Dominko, R.; Erakca, M.; Franco, A.A.; et al. Rechargeable Batteries of the Future—The State of the Art from a BATTERY 2030+ Perspective. *Adv. Energy Mater.* **2021**, *12*, https://doi.org/10.1002/aenm.202102904.

[10] Malinauskaite, J.; Anguilano, L.; Rivera, X.S. Circular waste management of electric vehicle batteries: Legal and technical perspectives from the EU and the UK post Brexit. *Int. J. Thermofluids* **2021**, *10*, 100078, https://doi.org/10.1016/j.ijft.2021.100078.

[11] Birkl, C.R.; Roberts, M.R.; McTurk, E.; Bruce, P.G.; Howey, D.A. Degradation diagnostics for lithium ion cells. *J. Power Sources* **2017**, *341*, 373–386, https://doi.org/10.1016/j.jpowsour.2016.12.011.

[12] Blanc, F.; Leskes, M.; Grey, C.P. In situ solid-state NMR spectroscopy of electrochemical cells: batteries, supercapacitors, and fuel cells. *Acc. Chem. Res.* **2013**, *46*, 1952–1963, https://doi.org/10.1021/ar400022u.

[13] Ilott, A.J.; Mohammadi, M.; Schauerman, C.M.; Ganter, M.J.; Jerschow, A. Rechargeable lithium-ion cell state of charge and defect detection by in-situ inside-out magnetic resonance imaging. *Nat. Commun.* **2018**, *9*, 1–7, https://doi.org/10.1038/s41467-018-04192-x.

[14] Sathiya, M.; Leriche, J.-B.; Salager, E.; Gourier, D.; Tarascon, J.-M.; Vezin, H. Electron paramagnetic resonance imaging for real-time monitoring of Li-ion batteries. *Nat. Commun.* **2015**, *6*, 6276, https://doi.org/10.1038/ncomms7276.

[15] Huang, J.Y.; Zhong, L.; Wang, C.M.; Sullivan, J.P.; Xu, W.; Zhang, L.Q.; Mao, S.X.; Hudak, N.S.; Liu, X.H.; Subramanian, A.; et al. In Situ Observation of the Electrochemical Lithiation of a Single SnO_2 Na nowire Electrode. *Science* **2010**, *330*, 1515–1520, https://doi.org/10.1126/science.1195628.

[16] Li, W.; Lutz, D.M.; Wang, L.; Takeuchi, K.J.; Marschilok, A.C.; Takeuchi, E.S. Peering into Batteries: E lectrochemical Insight Through In Situ and Operando Methods over Multiple Length Scales. *Joule* **2020**, *5*, 77–88, https://doi.org/10.1016/j.joule.2020.11.003.

[17] Spitthoff, L.; Shearing, P.R.; Burheim, O.S. Temperature, Ageing and Thermal Management of Lithium-Ion Batteries. *Energies* **2021**, *14*, 1248, https://doi.org/10.3390/en14051248.

[18] Knobloch, A.; Kapusta, C.; Karp, J.; Plotnikov, Y.; Siegel, J.B.; Stefanopoulou, A.G. Fabrication of Mult imeasurand Sensor for Monitoring of a Li-Ion Battery. *J. Electron. Packag.* **2018**, *140*, 031002, https://do i.org/10.1115/1.4039861.

[19] Amietszajew, T.; Fleming, J.; Roberts, A.J.; Widanage, W.D.; Greenwood, D.; Kok, M.D.; Pham, M.; Br ett, D.J.; Shearing, P.R.; Bhagat, R. Hybrid Thermo-Electrochemical In Situ Instrumentation for Lithium -Ion Energy Storage. *Batteries Supercaps* **2019**, 2, 934–940. https://doi.org/10.1002/batt.201900109.

[20] Martiny, N.; Rheinfeld, A.; Geder, J.; Wang, Y.; Kraus, W.; Jossen, A. Development of an All Kapton-B ased Thin-Film Thermocouple Matrix for In Situ Temperature Measurement in a Lithium Ion Pouch Cell. *IEEE Sensors J.* **2014**, *14*, 3377–3384, https://doi.org/10.1109/jsen.2014.2331996.

[21] Li, S.; Kirkaldy, N.; Zhang, C.; Gopalakrishnan, K.; Amietszajew, T.; Diaz, L.B.; Barreras, J.V.; Shams, M.; Hua, X.; Patel, Y.; et al. Optimal cell tab design and cooling strategy for cylindrical lithium-ion batte ries. *J. Power Sources* **2021**, *492*, 229594, https://doi.org/10.1016/j.jpowsour.2021.229594.

[22] Nascimento, M.; Novais, S.; Ding, M.S.; Ferreira, M.S.; Koch, S.; Passerini, S.; Pinto, J.L. Internal strain and temperature discrimination with optical fiber hybrid sensors in Li-ion batteries. *J. Power Sources* **20 18**, *410-411*, 1–9, https://doi.org/10.1016/j.jpowsour.2018.10.096.

[23] Edström, K.; Dominko, R.; Fichtner, M.; Perraud, S. Battery 2030+ Roadmap. **2020**, https://doi.org/10.3 3063/diva2-1452023.

[24] Raijmakers, L.; Danilov, D.; Eichel, R.-A.; Notten, P. A review on various temperature-indication metho ds for Li-ion batteries. *Appl. Energy* **2019**, *240*, 918–945, https://doi.org/10.1016/j.apenergy.2019.02.078.

[25] Bolsinger, C.; Birke, K.P. Effect of different cooling configurations on thermal gradients inside cylindric al battery cells. *J. Energy Storage* **2019**, *21*, 222–230, https://doi.org/10.1016/j.est.2018.11.030.

[26] Zhao, R.; Zhang, S.; Gu, J.; Liu, J.; Carkner, S.; Lanoue, E. An experimental study of lithium ion battery thermal management using flexible hydrogel films. *J. Power Sources* **2014**, *255*, 29–36, https://doi.org/1 0.1016/j.jpowsour.2013.12.138.

[27] Wang, P.; Zhang, X.; Yang, L.; Zhang, X.; Yang, M.; Chen, H.; Fang, D. Real-time monitoring of intern al temperature evolution of the lithium-ion coin cell battery during the charge and discharge process. *Ext reme Mech. Lett.* **2016**, *9*, 459–466, https://doi.org/10.1016/j.eml.2016.03.013.

[28] Samad, N.A.; Siegel, J.B.; Stefanopoulou, A.G.; Knobloch, A. Observability analysis for surface sensor l ocation in encased battery cells. In Proceedings of 2015 American Control Conference (ACC), Chicago, IL, USA, 1–3 July 2015, https://doi.org/10.1109/acc.2015.7170752.

[29] Robinson, J.B.; Shearing, P.R.; Brett, D.J.L. Thermal Imaging of Electrochemical Power Systems: A Rev iew. *J. Imaging* **2016**, *2*, 2, https://doi.org/10.3390/jimaging2010002.

[30] Goutam, S.; Timmermans, J.-M.; Omar, N.; Bossche, P.V.D.; Van Mierlo, J. Comparative Study of Surfa ce Temperature Behavior of Commercial Li-Ion Pouch Cells of Different Chemistries and Capacities by Infrared Thermography. *Energies* **2015**, *8*, 8175–8192, https://doi.org/10.3390/en8088175.

[31] Cheng, X.; Pecht, M. In Situ Stress Measurement Techniques on Li-ion Battery Electrodes: A Review. *E nergies* **2017**, *10*, 591, https://doi.org/10.3390/en10050591.

[32] Wang, X.; Sone, Y.; Segami, G.; Naito, H.; Yamada, C.; Kibe, K. Understanding Volume Change in Lith ium-Ion Cells during Charging and Discharging Using In Situ Measurements. *J. Electrochem. Soc.* **2007**, *154*, A14–A21, https://doi.org/10.1149/1.2386933.

[33] Cannarella, J.; Arnold, C.B. Stress evolution and capacity fade in constrained lithium-ion pouch cells. *J. Power Sources* **2014**, *245*, 745–751, https://doi.org/10.1016/j.jpowsour.2013.06.165.

[34] Lamb, J.; Orendorff, C.J.; Steele, L.A.M.; Spangler, S.W. Failure propagation in multi-cell lithium ion ba tteries. *J. Power Sources* **2015**, *283*, 517–523, https://doi.org/10.1016/j.jpowsour.2014.10.081.

[35] Yu, X.; Feng, Z.; Ren, Y.; Henn, D.; Wu, Z.; An, K.; Wu, B.; Fau, C.; Li, C.; Harris, S.J. Simultaneous O perando Measurements of the Local Temperature, State of Charge, and Strain inside a Commercial Lithi

um-Ion Battery Pouch Cell. *J. Electrochem. Soc.* **2018**, *165*, A1578–A1585, https://doi.org/10.1149/2.1251807jes.
[36] Hannan, M.A.; Lipu, M.S.H.; Hussain, A.; Mohamed, A. A review of lithium-ion battery state of charge estimation and management system in electric vehicle applications: Challenges and recommendations. *Renew. Sustain. Energy Rev.* **2017**, *78*, 834–854, https://doi.org/10.1016/j.rser.2017.05.001.
[37] Berecibar, M.; Gandiaga, I.; Villarreal, I.; Omar, N.; Van Mierlo, J.; van den Bossche, P. Critical review of state of health estimation methods of Li-ion batteries for real applications. *Renew. Sustain. Energy Rev.* **2016**, *56*, 572–587, https://doi.org/10.1016/j.rser.2015.11.042.
[38] Westerhoff, U.; Kroker, T.; Kurbach, K.; Kurrat, M. Electrochemical impedance spectroscopy based estimation of the state of charge of lithium-ion batteries. *J. Energy Storage* **2016**, *8*, 244–256, https://doi.org/10.1016/j.est.2016.09.001.
[39] Deng, Z.; Hu, X.; Lin, X.; Xu, L.; Che, Y.; Hu, L. General Discharge Voltage Information Enabled Health Evaluation for Lithium-Ion Batteries. *IEEE/ASME Trans. Mechatronics* **2020**, *26*, 1295–1306, https://doi.org/10.1109/tmech.2020.3040010.
[40] Deng, Z.; Hu, X.; Lin, X.; Che, Y.; Xu, L.; Guo, W. Data-driven state of charge estimation for lithium-ion battery packs based on Gaussian process regression. *Energy* **2020**, *205*, 118000, https://doi.org/10.1016/j.energy.2020.118000.
[41] Shu, X.; Shen, J.; Li, G.; Zhang, Y.; Chen, Z.; Liu, Y. A Flexible State-of-Health Prediction Scheme for Lithium-Ion Battery Packs with Long Short-Term Memory Network and Transfer Learning. *IEEE Trans. Transp. Electrification* **2021**, *7*, 2238–2248, https://doi.org/10.1109/tte.2021.3074638.
[42] Mehdi, B.L.; Qian, J.; Nasybulin, E.; Park, C.; Welch, D.A.; Faller, R.; Mehta, H.; Henderson, W.A.; Xu, W.; Wang, C.M.; et al. Observation and Quantification of Nanoscale Processes in Lithium Batteries by Operando Electrochemical (S)TEM. *Nano Lett.* **2015**, *15*, 2168–2173, https://doi.org/10.1021/acs.nanolett.5b00175.
[43] Li, Y.; Li, Y.; Pei, A.; Yan, K.; Sun, Y.; Wu, C.-L.; Joubert, L.-M.; Chin, R.; Koh, A.L.; Yu, Y.; et al. Atomic structure of sensitive battery materials and interfaces revealed by cryo–electron microscopy. *Science* **2017**, *358*, 506–510, https://doi.org/10.1126/science.aam6014.
[44] Nascimento, M.; Ferreira, M.S.; Pinto, J.L. Simultaneous Sensing of Temperature and Bi-Directional Strain in a Prismatic Li-Ion Battery. *Batteries* **2018**, *4*, 23, https://doi.org/10.3390/batteries4020023.
[45] Lao, J.; Sun, P.; Liu, F.; Zhang, X.; Zhao, C.; Mai, W.; Guo, T.; Xiao, G.; Albert, J. In situ plasmonic optical fiber detection of the state of charge of supercapacitors for renewable energy storage. *Light. Sci. Appl.* **2018**, *7*, 1–11, https://doi.org/10.1038/s41377-018-0040-y.
[46] Huang, J.; Blanquer, L.A.; Bonefacino, J.; Logan, E.R.; Corte, D.A.D.; Delacourt, C.; Gallant, B.M.; Boles, S.T.; Dahn, J.R.; Tam, H.-Y.; et al. Operando decoding of chemical and thermal events in commercial Na(Li)-ion cells via optical sensors. *Nat. Energy* **2020**, *5*, 674–683, https://doi.org/10.1038/s41560-020-0665-y.
[47] Mutyala, M.S.K.; Zhao, J.; Li, J.; Pan, H.; Yuan, C.; Li, X. In-situ temperature measurement in lithium ion battery by transferable flexible thin film thermocouples. *J. Power Sources* **2014**, *260*, 43–49, https://doi.org/10.1016/j.jpowsour.2014.03.004.
[48] Goutam, S.; Omar, N.; Bossche, P.V.D.; Van Mierlo, J.; Rodriguez, L.M.; Nerea, N.; Swierczynski, M.J. Surface Temperature evolution and the location of maximum and average surface temperature of a lithium-ion pouch cell under variable load profiles. In Proceedings of the EEVC European Electric Vehicle Congress EEVC-2014, Brussels, Belgium, 2–5 December, 2014, https://doi.org/10.13140/2.1.1506.9763.
[49] Louli, A.; Ellis, L.; Dahn, J. Operando Pressure Measurements Reveal Solid Electrolyte Interphase Growth to Rank Li-Ion Cell Performance. *Joule* **2019**, *3*, 745–761, https://doi.org/10.1016/j.joule.2018.12.009.
[50] Hu, X.; Yuan, H.; Zou, C.; Li, Z.; Zhang, L. Co-Estimation of State of Charge and State of Health for Lithium-Ion Batteries Based on Fractional-Order Calculus. *IEEE Trans. Veh. Technol.* **2018**, *67*, 10319–10329, https://doi.org/10.1109/tvt.2018.2865664.
[51] Rahimi-Eichi, H.; Ojha, U.; Baronti, F.; Chow, M.-Y. Battery Management System: An Overview of Its Application in the Smart Grid and Electric Vehicles. *IEEE Ind. Electron. Mag.* **2013**, *7*, 4–16, https://doi.org/10.1109/mie.2013.2250351.
[52] Lu, L.; Han, X.; Li, J.; Hua, J.; Ouyang, M. A review on the key issues for lithium-ion battery management in electric vehicles. *J. Power Sources* **2013**, *226*, 272–288, https://doi.org/10.1016/j.jpowsour.2012.10.060.

[53] Jiang, J.; Zhang, C. *Fundamentals and Applications of Lithium-Ion Batteries in Electric Drive Vehicles*; John Wiley & Sons Singapore Pte Ltd.: Singapore, 2015, https://doi.org/10.1002/9781118414798.

[54] Hu, X.; Zou, C.; Zhang, C.; Li, Y. Technological Developments in Batteries: A Survey of Principal Roles, Types, and Management Needs. *IEEE Power Energy Mag.* **2017**, *15*, 20–31, https://doi.org/10.1109/mpe.2017.2708812.

[55] Ahmed, S.; Bloom, I.; Jansen, A.N.; Tanim, T.; Dufek, E.J.; Pesaran, A.; Burnham, A.; Carlson, R.B.; Dias, F.; Hardy, K.; et al. Enabling fast charging – A battery technology gap assessment. *J. Power Sources* **2017**, *367*, 250–262, https://doi.org/10.1016/j.jpowsour.2017.06.055.

[56] Zou, C.; Hu, X.; Wei, Z.; Wik, T.; Egardt, B. Electrochemical Estimation and Control for Lithium-Ion Battery Health-Aware Fast Charging. *IEEE Trans. Ind. Electron.* **2017**, *65*, 6635–6645, https://doi.org/10.1109/tie.2017.2772154.

[57] Hoque, M.; Hannan, M.; Mohamed, A.; Ayob, A. Battery charge equalization controller in electric vehicle applications: A review. *Renew. Sustain. Energy Rev.* **2016**, *75*, 1363–1385, https://doi.org/10.1016/j.rser.2016.11.126.

[58] Lee, Y.-S.; Cheng, M.-W. Intelligent Control Battery Equalization for Series Connected Lithium-Ion Battery Strings. *IEEE Trans. Ind. Electron.* **2005**, *52*, 1297–1307, https://doi.org/10.1109/tie.2005.855673.

[59] Dong, B.; Han, Y. A new architecture for battery charge equalization. In Proceedings of 2011 IEEE Energy Conversion Congress and Exposition, Phoenix, AZ, USA, 17–22 September 2011, https://doi.org/10.1109/ECCE.2011.6063871.

[60] Einhorn, M.; Guertlschmid, W.; Blochberger, T.; Kumpusch, R.; Permann, R.; Conte, F.V.; Kral, C.; Fleig, J. A Current Equalization Method for Serially Connected Battery Cells Using a Single Power Converter for Each Cell. *IEEE Trans. Veh. Technol.* **2011**, *60*, 4227–4237, https://doi.org/10.1109/tvt.2011.2168988.

[61] Manenti, A.; Abba, A.; Merati, A.; Savaresi, S.M.; Geraci, A. A new BMS architecture based on cell redundancy. *IEEE Trans. Ind. Electron.* **2011**, *58*, 4314-4322. https://doi.org/10.1109/TIE.2010.2095398.

[62] Qian, H.; Zhang, J.; Lai, J.-S.; Yu, W. A high-efficiency grid-tie battery energy storage system. *IEEE Trans. Power Electron.* **2010**, *26*, 886–896, https://doi.org/10.1109/tpel.2010.2096562.

[63] Yarlagadda, S.; Hartley, T.T.; Husain, I. A Battery Management System Using an Active Charge Equalization Technique Based on a DC/DC Converter Topology. *IEEE Trans. Ind. Appl.* **2013**, *49*, 2720–2729, https://doi.org/10.1109/tia.2013.2264794.

[64] Zhao, X.; Zhang, Z.; Yang, S.; Liang, G. Inorganic ceramic fiber separator for electrochemical and safety performance improvement of lithium-ion batteries. *Ceram. Int.* **2017**, *43*, 14775–14783, https://doi.org/10.1016/j.ceramint.2017.07.219.

[65] Wang, Z.; Xiang, H.; Wang, L.; Xia, R.; Nie, S.; Chen, C.; Wang, H. A paper-supported inorganic composite separator for high-safety lithium-ion batteries. *J. Membr. Sci.* **2018**, *553*, 10–16, https://doi.org/10.1016/j.memsci.2018.02.040.

[66] Wang, Y.; Wang, S.; Fang, J.; Ding, L.-X.; Wang, H. A nano-silica modified polyimide nanofiber separator with enhanced thermal and wetting properties for high safety lithium-ion batteries. *J. Membr. Sci.* **2017**, *537*, 248–254, https://doi.org/10.1016/j.memsci.2017.05.023.

[67] Peng, P.; Jiang, F. Thermal safety of lithium-ion batteries with various cathode materials: A numerical study. *Int. J. Heat Mass Transf.* **2016**, *103*, 1008–1016, https://doi.org/10.1016/j.ijheatmasstransfer.2016.07.088.

[68] Qian, G.; Wang, L.; Shang, Y.; He, X.; Tang, S.; Liu, M.; Li, T.; Zhang, G.; Wang, J. Polyimide Binder: A Facile Way to Improve Safety of Lithium Ion Batteries. *Electrochimica Acta* **2015**, *187*, 113–118, https://doi.org/10.1016/j.electacta.2015.11.019.

[69] von Aspern, N.; Röser, S.; Rad, B.R.; Murmann, P.; Streipert, B.; Mönnighoff, X.; Tillmann, S.D.; Shevchuk, M.; Stubbmann-Kazakova, O.; Röschenthaler, G.V; et, al. Phosphorus additives for improving high voltage stability and safety of lithium ion batteries. *J. Fluor. Chem.* **2017**, *198*, 24–33, https://doi.org/10.1016/j.jfluchem.2017.02.005.

[70] Noelle, D.J.; Shi, Y.; Wang, M.; Le, A.V.; Qiao, Y. Aggressive electrolyte poisons and multifunctional fluids comprised of diols and diamines for emergency shutdown of lithium-ion batteries. *J. Power Sources* **2018**, *384*, 93–97, https://doi.org/10.1016/j.jpowsour.2018.02.068.

[71] Nelson, V. Fault-tolerant computing: fundamental concepts. *Computer* **1990**, *23*, 19–25, https://doi.org/10.1109/2.56849.

[72] Agarwal, A. Minimizing Building Energy Waste by Detecting and Addressing HVAC Issues. In *Soft Computing: Theories and Applications: Proceedings of SoCTA 2022*. Springer Nature Singapore: Singapore, 2023, pp.755–764.

[73] Chen, Z.; Zheng, C.; Lin, T.; Yang, Q. Multifault Diagnosis of Li-Ion Battery Pack Based on Hybrid System. *IEEE Trans. Transp. Electrification* **2021**, *8*, 1769–1784, https://doi.org/10.1109/tte.2021.3121036.

[74] Jiang, J.; Li, T.; Chang, C.; Yang, C.; Liao, L. Fault diagnosis method for lithium-ion batteries in electric vehicles based on isolated forest algorithm. *J. Energy Storage* **2022**, *50*, https://doi.org/10.1016/j.est.2022.104177.

[75] Zhang, Y.; Jiang, M.; Zhou, Y.; Zhao, S.; Yuan, Y. Towards High-Safety Lithium-Ion Battery Diagnosis Methods. *Batteries* **2023**, *9*, 63, https://doi.org/10.3390/batteries9010063.

[76] Qiu, Y.; Cao, W.; Peng, P.; Jiang, F. A novel entropy-based fault diagnosis and inconsistency evaluation approach for lithium-ion battery energy storage systems. *J. Energy Storage* **2021**, *41*, 102852, https://doi.org/10.1016/j.est.2021.102852.

[77] Yang, J.; Jung, J.; Ghorbanpour, S.; Han, S. Data–Driven Fault Diagnosis and Cause Analysis of Battery Pack with Real Data. *Energies* **2022**, *15*, 1647, https://doi.org/10.3390/en15051647.

[78] Wang, Y.; Zhou, C.; Zhao, G.; Chen, Z. A framework for battery internal temperature and state-of-charge estimation based on fractional-order thermoelectric model. *Trans. Inst. Meas. Control.* **2022**, https://doi.org/10.1177/01423312211067293.

[79] Chen, L.; Wang, H.; Li, Y.; Zhang, M.; Huang, J.; Pan, H. Battery state-of-health estimation by using metabolic extreme learning machine. *Automot. Eng.* **2021**, 43, 10–18.

[80] Jiang, J.; Cong, X.; Li, S.; Zhang, C.; Zhang, W.; Jiang, Y. A Hybrid Signal-Based Fault Diagnosis Method for Lithium-Ion Batteries in Electric Vehicles. *IEEE Access* **2021**, *9*, 19175–19186, https://doi.org/10.1109/access.2021.3052866.

[81] Held, M.; Brönnimann, R. Safe cell, safe battery? Battery fire investigation using FMEA, FTA and practical experiments. *Microelectron. Reliab.* **2016**, *64*, 705–710, https://doi.org/10.1016/j.microrel.2016.07.051.

[82] Rivera-Barrera, J.P.; Muñoz-Galeano, N.; Sarmiento-Maldonado, H.O. SoC estimation for lithium-ion batteries: Review and future challenges. *Electronics* **2017**, *6*, 102, https://doi.org/10.3390/electronics6040102.

[83] Popp, H.; Koller, M.; Jahn, M.; Bergmann, A. Mechanical methods for state determination of Lithium-Ion secondary batteries: A review. *J. Energy Storage* **2020**, *32*, 101859, https://doi.org/10.1016/j.est.2020.101859.

[84] Lu, Y.; Wang, X.; Mao, S.; Wang, D.; Sun, D.; Sun, Y.; Su, A.; Zhao, C.; Han, X.; Li, K.; et al. Smart Batteries Enabled by Implanted Flexible Sensors. *Energy Environ. Sci.* **2023**, https://doi.org/10.1039/D3EE00695F.

[85] Dam, S.K.; John, V. High-Resolution Converter for Battery Impedance Spectroscopy. *IEEE Trans. Ind. Appl.* **2017**, *54*, 1502–1512, https://doi.org/10.1109/tia.2017.2771498.

[86] Hoshi, Y.; Yakabe, N.; Isobe, K.; Saito, T.; Shitanda, I.; Itagaki, M. Wavelet transformation to determine impedance spectra of lithium-ion rechargeable battery. *J. Power Sources* **2016**, *315*, 351–358, https://doi.org/10.1016/j.jpowsour.2016.03.048.

[87] Wang, X.; Wei, X.; Chen, Q.; Dai, H. A Novel System for Measuring Alternating Current Impedance Spectra of Series-Connected Lithium-Ion Batteries with a High-Power Dual Active Bridge Converter and Distributed Sampling Units. *IEEE Trans. Ind. Electron.* **2020**, *68*, 7380–7390, https://doi.org/10.1109/tie.2020.3001841.

[88] Tasić, Z.; Mihajlović, M.B.P.; Radovanović, M.B.; Simonović, A.T.; Medić, D.V.; Antonijević, M.M. Electrochemical determination of L-tryptophan in food samples on graphite electrode prepared from waste batteries. *Sci. Rep.* **2022**, *12*, https://doi.org/10.1038/s41598-022-09472-7.

[89] Dai, H.; Yu, C.; Wei, X.; Sun, Z. State of charge estimation for lithium-ion pouch batteries based on stress measurement. *Energy* **2017**, *129*, 16–27, https://doi.org/10.1016/j.energy.2017.04.099.

[90] Hickey, R.; Jahns, T.M. Measuring Individual Battery Dimensional Changes for State-of-Charge Estimation using Strain Gauge Sensors. **2019**, 2460–2465, https://doi.org/10.1109/ecce.2019.8912578.

[91] Cannarella, J.; Arnold, C.B. State of health and charge measurements in lithium-ion batteries using mechanical stress. *J. Power Sources* **2014**, *269*, 7–14, https://doi.org/10.1016/j.jpowsour.2014.07.003.

[92] Dotoli, M.; Rocca, R.; Giuliano, M.; Nicol, G.; Parussa, F.; Baricco, M.; Ferrari, A.M.; Nervi, C.; Sgroi, M.F. A Review of Mechanical and Chemical Sensors for Automotive Li-Ion Battery Systems. *Sensors* **2022**, *22*, 1763, https://doi.org/10.3390/s22051763.

[93] Kirchev, A.; Guillet, N.; Brun-Buission, D.; Gau, V. Li-Ion Cell Safety Monitoring Using Mechanical Parameters: Part I. Normal Battery Operation. *J. Electrochem. Soc.* **2022**, *169*, 010515, https://doi.org/10.1149/1945-7111/ac48c8.

[94] Oca, L.; Guillet, N.; Tessard, R.; Iraola, U. Lithium-ion capacitor safety assessment under electrical abuse tests based on ultrasound characterization and cell opening. *J. Energy Storage* **2019**, *23*, 29–36, https://doi.org/10.1016/j.est.2019.02.033.

[95] Gold, L.; Bach, T.; Virsik, W.; Schmitt, A.; Müller, J.; Staab, T.E.; Sextl, G. Probing lithium-ion batteries' state-of-charge using ultrasonic transmission – Concept and laboratory testing. *J. Power Sources* **2017**, *343*, 536–544, https://doi.org/10.1016/j.jpowsour.2017.01.090.

[96] Ladpli, P.; Kopsaftopoulos, F.; Chang, F.-K. Estimating state of charge and health of lithium-ion batteries with guided waves using built-in piezoelectric sensors/actuators. *J. Power Sources* **2018**, *384*, 342–354, https://doi.org/10.1016/j.jpowsour.2018.02.056.

[97] Ohzuku, T.; Tomura, H.; Sawai, K. Monitoring of Particle Fracture by Acoustic Emission during Charge and Discharge of Li / MnO2 Cells. *J. Electrochem. Soc.* **1997**, *144*, 3496–3500, https://doi.org/10.1149/1.1838039.

[98] Didier-Laurent, S.; Idrissi, H.; Roué, L. In-situ study of the cracking of metal hydride electrodes by acoustic emission technique. *J. Power Sources* **2008**, *179*, 412–416, https://doi.org/10.1016/j.jpowsour.2007.12.073.

[99] Worrell, C.A.; Redfern, B.A.W. Acoustic emission studies of the breakdown of beta-alumina under conditions of sodium ion transport. *J. Mater. Sci.* **1978**, *13*, 1515–1520, https://doi.org/10.1007/bf00553208.

[100] Ohzuku, T.; Matoba, N.; Sawai, K. Direct evidence on anomalous expansion of graphite-negative electrodes on first charge by dilatometry. *J. Power Sources* **2001**, *97-98*, 73–77, https://doi.org/10.1016/s0378-7753(01)00590-0.

[101] Rhodes, K.J.; Dudney, N.J.; Lara-Curzio, E.; Daniel, C. Understanding the Degradation of Silicon Electrodes for Lithium-Ion Batteries Using Acoustic Emission. *J. Electrochem. Soc.* **2010**, *157*, A1354–A1360, https://doi.org/10.1149/1.3489374.

[102] Choe, C.-Y.; Jung, W.-S.; Byeon, J.-W. Damage Evaluation in Lithium Cobalt Oxide/Carbon Electrodes of Secondary Battery by Acoustic Emission Monitoring. *Mater. Trans.* **2015**, *56*, 269–273, https://doi.org/10.2320/matertrans.m2014396.

[103] Schweidler, S.; Bianchini, M.; Hartmann, P.; Brezesinski, T.; Janek, J. The Sound of Batteries: An Operando Acoustic Emission Study of the LiNiO 2 Cathode in Li–Ion Cells. *Batter. Supercaps* **2020**, https://doi.org/10.1002/batt.202000206.

[104] Sood, B.; Osterman, M.; Pecht, M. Health monitoring of lithium-ion batteries. In Proceedings of 2013 IEEE Symposium on Product Compliance Engineering (ISPCE), Austin, TX, USA, 7–9 October 2013, 10.1109/ISPCE.2013.6664165.

[105] Hsieh, A.G.; Bhadra, S.; Hertzberg, B.J.; Gjeltema, P.J.; Goy, A.; Fleischer, J.W.; Steingart, D.A. Electrochemical-acoustic time of flight: in operando correlation of physical dynamics with battery charge and health. *Energy Environ. Sci.* **2015**, *8*, 1569–1577, https://doi.org/10.1039/c5ee00111k.

[106] Robinson, J.B.; Maier, M.; Alster, G.; Compton, T.; Brett, D.J.L.; Shearing, P.R. Spatially resolved ultrasound diagnostics of Li-ion battery electrodes. *Phys. Chem. Chem. Phys.* **2018**, *21*, 6354–6361, https://doi.org/10.1039/c8cp07098a.

[107] Robinson, J.B.; Owen, R.E.; Kok, M.D.R.; Maier, M.; Majasan, J.; Braglia, M.; Stocker, R.; Amietszajew, T.; Roberts, A.J.; Bhagat, R.; et al. Identifying Defects in Li-Ion Cells Using Ultrasound Acoustic Measurements. *J. Electrochem. Soc.* **2020**, *167*, 120530, https://doi.org/10.1149/1945-7111/abb174.

[108] Davies, G.; Knehr, K.W.; Van Tassell, B.; Hodson, T.; Biswas, S.; Hsieh, A.G.; Steingart, D.A. State of Charge and State of Health Estimation Using Electrochemical Acoustic Time of Flight Analysis. *J. Electrochem. Soc.* **2017**, *164*, A2746–A2755, https://doi.org/10.1149/2.1411712jes.

[109] Deng, Z.; Huang, Z.; Shen, Y.; Huang, Y.; Ding, H.; Luscombe, A.; Johnson, M.; Harlow, J.E.; Gauthier, R.; Dahn, J.R. Ultrasonic scanning to observe wetting and "unwetting" in Li-ion pouch cells. *Joule* **2020**, *4*, 2017–2029, https://doi.org/10.1016/j.joule.2020.07.014.

[110] Louli, A.J.; Eldesoky, A.; Weber, R.; Genovese, M.; Coon, M.; Degooyer, J.; Deng, Z.; White, R.T.; Lee, J.; Rodgers, T.; et al. Diagnosing and correcting anode-free cell failure via electrolyte and morphological analysis. *Nat. Energy* **2020**, *5*, 693–702, https://doi.org/10.1038/s41560-020-0668-8.

[111] Spillman Jr, W.B. Fiber optic biosensors. In *Fiber Optic Sensors: An Introduction for Engineers and Scie ntists*. John Wiley & Sons: Hoboken, NJ, USA, 2011, pp.451-490.

[112] David, N.A.; Wild, P.M.; Jensen, J.; Navessin, T.; Djilali, N. Simultaneous In Situ Measurement of Tem perature and Relative Humidity in a PEMFC Using Optical Fiber Sensors. *J. Electrochem. Soc.* **2010**, *15 7*, B1173–B1179, https://doi.org/10.1149/1.3436652.

[113] Han, G.; Yan, J.; Guo, Z.; Greenwood, D.; Marco, J.; Yu, Y. A review on various optical fibre sensing m ethods for batteries. *Renew. Sustain. Energy Rev.* **2021**, *150*, 111514, https://doi.org/10.1016/j.rser.2021. 111514.

[114] Su, Y.-D.; Preger, Y.; Burroughs, H.; Sun, C.; Ohodnicki, P.R. Fiber Optic Sensing Technologies for Bat tery Management Systems and Energy Storage Applications. *Sensors* **2021**, *21*, 1397, https://doi.org/10.3 390/s21041397.

[115] Raghavan, A.; Kiesel, P.; Sommer, L.W.; Saha, B.; Sahu, S.K.; Lochbaum, A.; Staudt, T.; Bae, C.J.; Ala mgir, M., Hah, H.J; et, al. Embedded fiber optic cables for battery management. U.S. Patent No. 10,446,8 86. 15 October 2019.

[116] Leitão, C.; Novo, C.; Yang, G.; Tang, C.; Pinto, J.L. Fiber Bragg grating sensors novel applications. In P roceedings of Latin America Optics and Photonics Conference 2012, Sao Sebastiao, Brazil, 10–13 Nove mber 2012, https://doi.org/10.1364/LAOP.2012.LS2C.1.

[117] Yang, G.; Leitão, C.; Li, Y.; Pinto, J.; Jiang, X. Real-time temperature measurement with fiber Bragg sen sors in lithium batteries for safety usage. *Measurement* **2013**, *46*, 3166–3172, https://doi.org/10.1016/j.m easurement.2013.05.027.

[118] Nascimento, M.; Paixão, T.; Ferreira, M.S.; Pinto, J.L. Thermal Mapping of a Lithium Polymer Batteries Pack with FBGs Network. *Batteries* **2018**, *4*, 67, https://doi.org/10.3390/batteries4040067.

[119] Huang, J.; Blanquer, L.A.; Gervillie, C.; Tarascon, J.-M. Distributed Fiber Optic Sensing to Assess In-Li ve Temperature Imaging Inside Batteries: Rayleigh and FBGs. *J. Electrochem. Soc.* **2021**, https://doi.org/ 10.1149/1945-7111/ac03f0.

[120] Fleming, J.; Amietszajew, T.; McTurk, E.; Towers, D.P.; Greenwood, D.; Bhagat, R. Development and e valuation of in-situ instrumentation for cylindrical Li-ion cells using fibre optic sensors. *Hardwarex* **2018**, *3*, 100–109, https://doi.org/10.1016/j.ohx.2018.04.001.

[121] Raghavan, A.; Kiesel, P.; Sommer, L.W.; Schwartz, J.; Lochbaum, A.; Hegyi, A.; Schuh, A.; Arakaki, K.; Saha, B.; Ganguli, A.; et al. Embedded fiber-optic sensing for accurate internal monitoring of cell state i n advanced battery management systems part 1: Cell embedding method and performance. *J. Power Sour ces* **2016**, *341*, 466–473, https://doi.org/10.1016/j.jpowsour.2016.11.104.

[122] Ganguli, A.; Saha, B.; Raghavan, A.; Kiesel, P.; Arakaki, K.; Schuh, A.; Schwartz, J.; Hegyi, A.; Somme r, L.W.; Lochbaum, A.; et al. Embedded fiber-optic sensing for accurate internal monitoring of cell state in advanced battery management systems part 2: Internal cell signals and utility for state estimation. *J. P ower Sources* **2017**, *341*, 474–482, https://doi.org/10.1016/j.jpowsour.2016.11.103.

[123] Bae, C.-J.; Manandhar, A.; Kiesel, P.; Raghavan, A. Monitoring the Strain Evolution of Lithium-Ion Batt ery Electrodes using an Optical Fiber Bragg Grating Sensor. *Energy Technol.* **2016**, *4*, 851–855, https://d oi.org/10.1002/ente.201500514.

[124] Downie, L.E.; Dahn, J.R. Determination of the Voltage Dependence of Parasitic Heat Flow in Lithium Io n Cells Using Isothermal Microcalorimetry. *J. Electrochem. Soc.* **2014**, *161*, A1782–A1787, https://doi.o rg/10.1149/2.0301412jes.

[125] Desai, P.; Huang, J.; Hijazi, H.; Zhang, L.; Mariyappan, S.; Tarascon, J. Deciphering Interfacial Reaction s via Optical Sensing to Tune the Interphase Chemistry for Optimized Na-Ion Electrolyte Formulation. *A dv. Energy Mater.* **2021**, *11*, https://doi.org/10.1002/aenm.202101490.

[126] Wahl, M.S.; Spitthoff, L.; Muri, H.I.; Jinasena, A.; Burheim, O.S.; Lamb, J.J. The Importance of Optical Fibres for Internal Temperature Sensing in Lithium-ion Batteries during Operation. *Energies* **2021**, *14*, 3 617, https://doi.org/10.3390/en14123617.

[127] Ghannoum, A.; Norris, R.C.; Iyer, K.; Zdravkova, L.; Yu, A.; Nieva, P.M. Optical Characterization of C ommercial Lithiated Graphite Battery Electrodes and in Situ Fiber Optic Evanescent Wave Spectroscopy. *ACS Appl. Mater. Interfaces* **2016**, *8*, 18763–18769, https://doi.org/10.1021/acsami.6b03638.

[128] Nedjalkov, A.; Meyer, J.; Gräfenstein, A.; Schramm, B.; Angelmahr, M.; Schwenzel, J.; Schade, W. Refractive Index Measurement of Lithium Ion Battery Electrolyte with Etched Surface Cladding Waveguide Bragg Gratings and Cell Electrode State Monitoring by Optical Strain Sensors. *Batteries* **2019**, *5*, 30, https://doi.org/10.3390/batteries5010030.
[129] Marrec, L.; Bourgerette, T.; Datin, E.; Ferchaud, N.; Pucel, B.; Quetel, L.; Renault, C.; Tregoat, D. In-situ optical fibre sensors for temperature and salinity monitoring. **2005**, *2*, 1276, https://doi.org/10.1109/oceanse.2005.1513243.
[130] Guo, T.; Liu, F.; Guan, B.-O.; Albert, J. [INVITED] Tilted fiber grating mechanical and biochemical sensors. *Opt. Laser Technol.* **2016**, *78*, 19–33, https://doi.org/10.1016/j.optlastec.2015.10.007.
[131] Sharma, A.K.; Jha, R.; Gupta, B.D. Fiber-Optic Sensors Based on Surface Plasmon Resonance: A Comprehensive Review. *IEEE Sensors J.* **2007**, *7*, 1118–1129, https://doi.org/10.1109/jsen.2007.897946.
[132] Al Mahmud, R.; Sagor, R.; Khan, M. Surface plasmon refractive index biosensors: A review of optical fiber, multilayer 2D material and gratings, and MIM configurations. *Opt. Laser Technol.* **2023**, *159*, https://doi.org/10.1016/j.optlastec.2022.108939.
[133] Yamanaka, T.; Nakagawa, H.; Ochida, M.; Tsubouchi, S.; Domi, Y.; Doi, T.; Abe, T.; Ogumi, Z. Ultrafine Fiber Raman Probe with High Spatial Resolution and Fluorescence Noise Reduction. *J. Phys. Chem. C* **2016**, *120*, 2585–2591, https://doi.org/10.1021/acs.jpcc.5b11894.
[134] Fujimoto, S.; Uemura, S.; Imanishi, N.; Hirai, S. Oxygen concentration measurement in the porous cathode of a lithium-air battery using a fine optical fiber sensor. *Mech. Eng. Lett.* **2019**, *5*, 19–00095, https://doi.org/10.1299/mel.19-00095.
[135] Huang, J.; Boles, S.T.; Tarascon, J.-M. Sensing as the key to battery lifetime and sustainability. *Nat. Sustain.* **2022**, *5*, 194–204, https://doi.org/10.1038/s41893-022-00859-y.