Perspective on commercializing smart sensing for batteries

Xibin Lu[1,2,3], Jean-Marie Tarascon[4,5,6], Jiaqiang Huang[1,2,3]*

[1] The Hong Kong University of Science and Technology (Guangzhou), Sustainable Energy and Environment Thrust, Nansha, Guangzhou, Guangdong 511400, China.
[2] Department of IPO, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong Special Administrative Regions, China
[3] HKUST Shenzhen-Hong Kong Collaborative Innovation Research Institute, Futian, Shenzhen, Guangdong, China.
[4] Collège de France, Chimie du Solide et de l'Energie—UMR 8260 CNRS, Paris, France.
[5] Réseau sur le Stockage Electrochimique de l'Energie (RS2E)—FR, CNRS 3459, Amiens, France.
[6] Sorbonne Université–UPMC Paris 06, Paris, France.

* Corresponding author: J. Huang: seejhuang@ust.hk

Abstract

The battery is an indispensable puzzle in the current roadmap towards a carbon-neutral world. With the soaring production, the battery itself is unexpectedly becoming a sustainability problem for society. Increasing attention is thus placed on the life cycle of batteries entailing the second life and recycling of batteries, relying on the monitoring of batteries' state and the classification of retired batteries by sensors. Battery sensors that decode the fundamental physical/chemical processes are thus poised to maximize the quality, reliability, lifetime, and safety of batteries and to minimize the environmental footprint. Fiber optic sensors stand out by virtue of their miniature size, insulating nature, electromagnetic immunity, and versatile sensitivities. In this Perspective, we discuss the promise and challenges of commercializing smart sensing for batteries and highlight how fiber optic sensors can synergize with paradigm shifts, including cell to pack and cell to chassis technologies.

Keywords: Batteries; Smart sensing; Fiber optic sensors; Sensor implanting; Smart batteries

Introduction

Batteries play a central role in reducing CO_2 emissions and reaching the ultimate goal of carbon neutrality, by moderating the intermittent renewable energy and fueling the electric vehicles (EVs). Beyond these "macro-level" benefits, the sustainability of the battery itself cannot be absent if carbon neutrality is to succeed[1]. This, in turn, necessitates the life-cycle monitoring/tracking of batteries towards a circular economy[2] that entails the second life and recycling of batteries. To realize the life-cycle "battery passport"[3], battery sensors, which decode the underlying physical/chemical processes into readable electrical/optical signals, become increasingly essential. In response, European Battery 2030+ roadmap[4] initiated the integration of smart sensing into batteries in 2020 via three funding projects (INSTABAT and

SENSIBAT for internal sensing, while SPARTACUS for external sensing) for monitoring paramount parameters of batteries under real-world operation.

The concept of battery sensor can trace back to 1887 by using a hydrometer for detecting the state of charge (SOC) of lead-acid batteries[5], that is, to "see" the remaining fuels in the tank. With the rapid expansion of battery applications and the market particularly of EVs[6], the states of interest extend to states of health (SOH), state of power (SOP), and state of safety (SOS). To monitor these states, diverse sensors are being developed and applied in batteries, including electrochemical, electric, acoustic, and optical sensors[1]. Fiber optic sensors stand out among others thanks to their small diameter (<200 μm and thus the low invasiveness), electrical insulating nature, and immunity to electromagnetic (EM) interference. Besides, the fiber optic sensors are versatile to monitor multiple observables of batteries, including temperature[7] (T), strain[8] (ε), pressure[7] (P), refractive index[9], and molecular fingerprints[1, 10].

The working mechanism and applications of battery sensors have been reviewed in detail previously[1]; however, the challenges and solutions of commercializing smart sensing for batteries remain less touched. To close this gap, we firstly reiterate the importance of smart sensing for a sustainable future. To select the right sensor, we then compare different battery sensors and highlight the superiority of fiber optic sensors in real applications. Lastly, we show how the fiber sensors can be implanted into batteries of different formats in addition to their compatibility with emerging engineering designs.

Do we need smart sensing for cells?

Driven by the increasing EV penetration, the global market for lithium-ion batteries[6] reached 266 GWh in 2020 and expectedly 2,500 GWh in 2030 (Figure 1a). Whereas providing positive impacts in reducing fossil fuel burning and CO_2 emission, the batteries themselves are becoming an inevitable sustainability problem[2] through their life cycle from mining, production, application, and retirement. For instance, >40 GWh batteries[6] were retired in 2019 (Figure 1b) and more in the foreseeable future. To lower the life-cycle footprint of batteries, in addition to the exploitation of material eco-designs, a circular, responsible battery value chain[2] calls for "greener" application, repurposing, and retirement, which in turn depend on the reliable monitoring/sensing of batteries' states (SOC, SOH, SOP, SOS, etc.). However, the current battery diagnoses turn out to be insufficient, as witnessed by monthly reports of auto-ignitions of EVs, which subsequently lead to the high safety margins and thus the under-utilization of batteries. Besides, the difficulties in estimating the retired batteries' SOH and SOS also prevent the second life of batteries from reality. Thus, the need to increase battery sensing is clear. However, the pursuit of "sensors per cell" concept remains controversial.

Hints are provided by the trendy engineering designs of batteries with increasing capacity and dimension of the single cell, see Figure 1c,d. The cylindrical cells (mainly adopted by Tesla) have transited from 18650 to 21700 and recently to 46800, rendering higher energy and power densities[11] by reducing the dead volumes. However, the benefits come at a cost that the spatial heterogeneity of temperature and current distribution inside the cell is exacerbated, with the simulation showing the agglomerations close to the central void[11], stressing the need for the sensing inside the cell. Besides, the enlarged cell size raises the inconsistency of cells inside a pack, pressing the necessity of sensing each cell. At the same time, the increased capacity/dimension from 18650 to 46800 (Figure 1c) makes every single cell a more expensive

asset from both economical and environmental perspectives, justifying the life-cycle sensing of a single cell. The increase in cell capacity can also be seen in prismatic cells (Figure 1d, data from BYD, China), despite their flexibility in format dimensions. The increased capacity of a single cell is accompanied by the decreased cell number in the pack (Figure 1e), and the sensor number is thus reduced even under the "one sensor per cell" scheme. Fewer interrogation units can be further achieved via multiplexing the optical sensors[12] (Figure 1e, right axis), cutting the sensing cost as discussed in the next session.

In addition to complying with the larger battery design, the success of commercializing battery sensors potentially depends on the economic profitability by maximizing the quality, reliability, lifetime, and safety (QRLS)[1] of batteries. However, the extended battery lifespan may exceed the need for a 10-year use of electric vehicles, and revenues must be consolidated from other scenarios of energy storage such as vehicles to grid (V2G), building (V2B), and vehicle (V2V), where information from sensors is the basis for the energy management. Aside from EVs being the decentralized energy blocks, the repurposing of retired EV batteries into less demanding applications (*e.g.*, grid, low-speed vehicles) further exploits the battery lifespan and again relies on the QRLS guaranteed by batteries sensors. Meanwhile, the battery sensors will benefit the classification of retired batteries into either repurposing or recycling by the life-long record, that is, "battery passport"[3]. Altogether, we argue that battery sensing will be one of the key puzzles towards increasingly economically and environmentally benign batteries (Figure 1f).

Financially, recent analyses[13, 14] show that the global market of automotive battery sensor was about 3 billion US dollars in 2020 and was anticipated to reach nearly 6 billion US dollars by 2027. Note that this anticipation is simply based on the conventional electrical sensors, and we can expect a much stronger growth if the concepts of smart sensing and "sensor per cell" are realized.

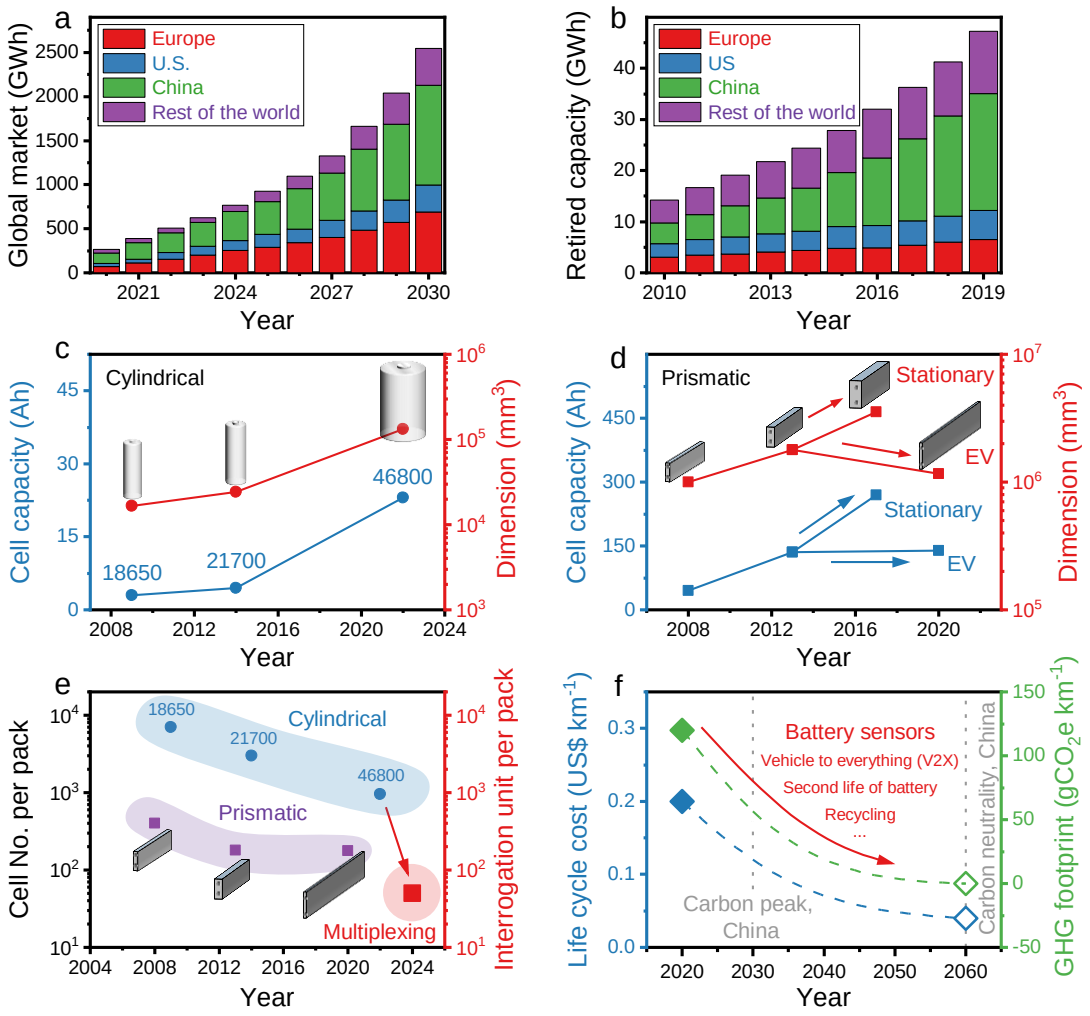


Figure 1 | Sensors for cells. a, The anticipated global market of lithium-ion batteries[6]. **b,** The capacity of retired lithium-ion batteries[6]. **c,d,** The evolutions of capacity and dimension of cylindrical (**c**) and prismatic (**d**) cells with lines as a guide to the eyes. The data is retrieved from the media releases from Tesla and BYD. The formats of prismatic cells in (**d**) include 356×100×28, 420×109.5×39, 416×146×58, 960×90×13.5 mm^3, from left to right. **e**, The evolution of cell number per pack (left axis) leading to reduced sensor/interrogation units (right axis). The shading indicates the uncertainties. **f**, Ambitions of battery sensors to reduce life cycle cost and green house gas (GHG) footprint of batteries. The data for 2020 refers to the literature[15], while the data for 2060 and the dashed curves are estimated to show the trend for meeting China's goals of carbon peak in 2030 and carbon neutrality in 2060.

Comparison of battery sensors

Diverse battery sensors are being explored to secure their position in the final commercialization. In this session, we briefly discuss the strengths of different sensors in detecting various physical/chemical phenomena in batteries (Figure 2). We then further compare the other critical merits for real applications, justifying the superiority of fiber optic sensors.

Electrochemical methods: Electrochemical methods lay the foundation for battery research/prototyping as well as the modern battery management system (BMS). They rely on

the measurements of current and voltage, which diversify into coulomb counting, coulombic efficiency, open-circuit voltage, electrochemical impedance spectroscopy (EIS), and derivative curves (dQ/dV and dV/dQ). These methods are practically adopted for estimating the SOC and SOH of batteries, while being inferior in sensing other observables such as temperature and strain.

Electrical sensors (*T*, *ε*, *P*): Due to the incapability of electrochemical methods to sense temperature, other electrical sensors (such as thermistors[16], thermocouples[17], or resistance temperature detectors[18]) appear as complements in real applications. In addition to temperature sensors, strain[19] and pressure[20] sensors have been explored to monitor the (ir-)reversible volume expansion of batteries.

Acoustics: Acoustic sensor relies on another type of electrical transducers/sensors, which convert electrical signals into mechanical waves or vice versa. Depending on the wave source, the acoustic battery sensing can be either passive[21] or active[22], while 2D mapping[23] can be achieved via a translational platform or sensor arrays. Through the interactions (*e.g.*, transmission, reflection) of the mechanical waves with the material, the mechanical events (*e.g.,* cracking) or properties (*e.g.,* modulus) of batteries can be "heard".

Fiber optics: Deviating from the above electrical sensors, fiber optic sensing exploits optical signals transmitting through optical fibers. The optical signal can be modulated through the various interactions (*e.g.,* diffraction, absorption, and scattering) of light with matters, offering diverse sensing mechanisms.

Among them, fiber Bragg grating (FBG) stands out as a mature technology, being practically applied in other sectors (such as structural health monitoring in construction[24]). By inscribing periodic modifications on the fiber core, FBGs reflect light centering at a specific wavelength ($\lambda_B = 2n_{eff}\Lambda$, with n_{eff} and Λ being the effective refractive index of the grating and the grating period, respectively). This wavelength is sensitive to temperature, strain, and pressure variations of batteries, since these perturbations influence n_{eff} and Λ. The decoupling of the sensitivities depends on the delicate designs of implanting[7], packaging, or sensor combinations[7]. Because these perturbations pertain to the impedance buildup, volume expansion, and side reactions, FBGs are proved to be useful in estimating the SOC[25] and SOH[26] of batteries.

Unlike FBGs that confine the light inside the fiber core, tilted fiber Bragg grating (TFBG) frees parts of light from the core by tilting the Bragg grating. TFBGs utilize the evanescent wave penetrating into the environment, thus being additionally sensitive to the surrounding refractive index. By inserting TFBGs into the electrolyte and tracking its refractive index, we previously demonstrated[9] that TFBGs can monitor the electrolyte degradation. Besides, the turbidity of the electrolyte[9] was also detected via the optical scattering and absorptions of particles within the evanescent field. The multi-mode spectra of TFBG also offer extra ways to resolve the cross-sensitivities.

In spite of the valuable implications arising from refractive index and turbidity, the probed information is limited to particle level (0.1-10 μm)[1], and we thus remain blind to details at the lower length scale. To overcome this limit, a more sophisticated approach to exploiting the evanescent wave lies in the fiber optic spectroscopies, including Raman[10], infrared[1], and those[27] using visible light. They are able to capture the fingerprints of chemical molecules (for example, via the resonant frequencies of vibrational modes in infrared spectroscopy[1]) inside

the batteries, rendering more fundamental insights into the evolutions of states.

In comparison to electrical sensors, fiber optic sensors also provide the possibility of high spatial resolutions by either multiplexing (that is, quasi-distributed) or distributed sensing technology (*e.g.,* Rayleigh scattering sensing)[12, 28]. Namely, the multiplexing of a few FBGs into a single fiber provides the capability of spatially sensing only a few discontinuous, pre-defined locations[12], which is thus ascribed as "quasi-distributed"[24]. Alternatively, we previously showed that fully distributed fiber optic sensing based on Rayleigh scattering could monitor the temperature (or strain) variations continuously along the fiber (*i.e.,* every 0.65 mm) inside the batteries[12]. Despite the superior spatial resolution, this Rayleigh sensing technology relies on an even more expensive frequency-domain interrogator and gives a relatively low measurement repeatability[12] in comparison to the FBG technology.

Figure 2 (above the dashed line) summarizes the above discussion and qualitatively compares their sensing capabilities for battery applications. Aside from sensing capability, safety is the priority of batteries and the primary driving force for smart sensing. Turning to safety, two aspects need to be covered: (1) the additional safety risks from the sensors; (2) the added benefits from the sensors on improving the safety of batteries. As for (1), while the additional short circuits of batteries may arise from the electrical sensors, the application of tiny and insulating fiber optic sensors clearly suppress this possibility. Regarding (2), the improvements in batteries' safety depend again on the sensing capability of sensors and eventually on the way to exploit the sensing data, that is, the diagnostics/prognostics algorithms. As a pioneer exploration of FBG sensors[29], Pinto *et al.* showed that FBGs exhibited rapid thermal responses to overcharging and external short circuits. Combining (1) and (2), we believe FBGs are a better candidate than electrical sensors, while electrochemical methods are relatively weak in detecting safety issues. Nevertheless, a fundamental study is still in need to thoroughly quantify the individual and intertwined responses of different observables (*e.g., T*, ε, *P*) to these phenomena (*e.g.,* SOC and crack). Besides, to practically evaluate the effectiveness of smart sensing in diagnostics/prognostics, we should go for high-throughput experiments on commercial cells under diverse working conditions to acquire a large amount of data for statistical analysis as well as the training of diagnostic algorithms.

Towards commercialization, merits pertaining to the battery operation conditions should also be considered (Figure 2, below the dashed line). In high-voltage EV packs, the high voltage (up to 650 V) can shock the sensor and destroy the interrogation system if the sensor is electrically conductive. In this regard, optical fibers made of silica (or chalcogenide for infrared) are more suitable candidates owing to their insulator nature. Though appropriate insulations within the pack should be guaranteed anyway, we argue that the introduction of optical fiber will require less additional effort in insulation design. On the other hand, the optical fibers offer the possibility to sense the key locations (*e.g.*, directly on the cell can or even within the electrode) without being limited by the insulation layer. Furthermore, the high-voltage and high-power batteries (together with convertors and motors) also induce strong electromagnetic fields, leading to the malfunction (or high noise) of electrical sensors without proper electromagnetic shielding. On the contrary, the optical fibers are electromagnetically immune, rendering better reliability.

The durability of sensors is another vital factor for commercialization; however, it has rarely been investigated. To have a preliminary idea of the durability of different sensors, we did

a survey[30-32] on their applications in other fields, such as construction, see Figure 2. Surprisingly, it was predicted that fiber optical sensors could function for more than 20 years in civil composite applications[32], while all the other sensor candidates also showed the potential for long-term durability (>10 years)[30, 31]. In fact, we have recently shown that the TFBG sensors can function in 18650 cells for more than 1000 cycles[9]. However, we must confess that the experiments were done within one year at 25 °C and challenges are expected under real EV working conditions that combine vibration, high/low temperatures, and long duration (>10 years). Thus, we call for accelerated tests towards a careful investigation of the long-term durability of optical sensors under practical conditions.

The size of sensors is also critical for practical implementation. For example, it was reported[33] that the large-size implanted sensor not only influences the measurement accuracy but also pertains to some unwanted side effects (*e.g.*, blocking the lithium transportation) on the batteries. We, therefore, compare the size of different sensors in Figure 2, showing that the fiber optic sensors are the finest (10^{-3} to 10^{0} mm) among others. Consequently, fiber optic sensors are favored in terms of sensor implantation.

Phenomena	Electro -chemical	Electrical (T, ε, P)	Acoustics	FBG	TFBG	Fiber spectroscopy
SOC	🟢	🔴	🟡	🟡	🟡	🟡
SOH	🟢	🔴	🟡	🟡	🟡	🟡
Thermal	🔴	🟢	🔴	🟢	🟢	🔴
Strain	🔴	🟢	🟡	🟢	🟢	🔴
Pressure	🔴	🟢	🟡	🟢	🟡	🔴
Crack	🔴	🔴	🟢	🟡	🟡	🔴
Molecules	🔴	🔴	🔴	🔴	🟡	🟢
Safety	🔴	🟡	🟡	🟢	🟡	🟡
Insulator	🔴	🔴	🔴	🟢	🟢	🟢
EM interference	🔴	🔴	🔴	🟢	🟢	🟢
Max. Durability (Year)	>10	>10	>20	>20	R&D	R&D
Sensor size (mm)	10^{-1} to 10^{2}	10^{-1} to 10^{2}	10^{1} to 10^{2}	10^{-3} to 10^{0}	10^{-2} to 10^{0}	10^{-1} to 10^{0}
Sensor cost (US$ unit^{-1})	0	10^{0} to 10^{2}	10^{0} to 10^{2}	10^{0} to 10^{1}	10^{1} to 10^{2}	R&D
Interrogator cost (US$ unit^{-1})	0 to 10^{4}	10^{0} to 10^{2}	10^{3} to 10^{4}	10^{2} to 10^{4}	10^{3} to 10^{4}	10^{4} to 10^{5}

Degree of appropriateness: Green, strong; Yellow, medium or to be explored; Red, weak

Figure 2 | Benchmark of various battery sensors with respect to merits that are key for commercialization in batteries. Although it is subjective and prone to overestimation or underestimation, some battery sensors are clearly best-suited to capture specific phenomena. Note that the data of cost is surveyed by website/email/phone with mainly Chinese suppliers.

As cost can be the primary barrier to implementing these sensing technologies, we also survey the sensor cost (US$ per unit sensor) and the interrogator cost (US$ per unit channel) via website/email/phone, see Figure 2.

Starting from the basic electrochemical methods, simply measuring the time-resolved voltage/current does not require additional sensors or equipment to nowadays BMS. These time-series data can be further utilized for derivative curves (dQ/dV or dV/dQ). However, the onboard voltage/current meters only offer relatively low accuracies[34]. Thus, the pursuit of high-precision coulombic efficiency (0.01%) measurement necessitates a customized charger costing ~4000 US$, as reported by Dahn et al.[34]. Similarly, the EIS also needs expensive potentiostats (10^3 to 10^4 US$ per unit channel) with a wide alternating current (AC) frequency range. Meanwhile, electrical T, ε, and P sensors appear as affordable add-ins (10^0 to 10^2 US$ per sensor and 10 to 10^2 US$ per interrogation channel) to the electrochemical methods. On the contrary, acoustic sensing turns out to be costly (10^0 to 10^2 US$ per sensor and 10^3 to 10^4 US$ per interrogation channel), due mainly to the high-frequency (at MHz scale) pulser and receiver[22]. Noteworthily, to achieve high accuracy, the cables of the above-mentioned electrical sensors should be delicately protected from electromagnetic interference, rendering the extra wiring design/cost compulsory.

Surprisingly, the price of FBG sensors is comparable to (10^0 to 10^1 US$ per sensor) the one of counterparts - electrical T, ε, and P sensors, thanks to the mature fabrication techniques and the pre-existing markets in other sectors. Optimistically, the FBG can be much cheaper if its mass production for battery application is realized[35]. Nevertheless, the TFBGs have a much smaller market, thus offering a higher cost of 10^1 to 10^2 US$ per sensor. Meanwhile, we cannot find commercial suppliers for chalcogenide[1] and photonic crystal fibers[10] for fiber optic spectroscopies.

The main obstacle to commercializing fiber optic sensors in batteries seems to be the expensive optical interrogator, that is, 10^2 to 10^4, 10^3 to 10^4, and 10^4 to 10^5 US$ per channel for FBG, TFBG, and fiber spectroscopies, respectively. However, we notice that the commercially available interrogators for FBGs are often overdesigned, exceeding the needs of battery applications. For example, the interrogators normally offer a wavelength range of ~100 nm, namely, ~10,000 ^oC for FBG's (with a temperature sensitivity of ~10 pm $^oC^{-1}$)[7] temperature measurement range, much surpassing the working temperature range of batteries. Thus, the downgrading of wavelength range (and/or other performance) appears to feasibly reduce the cost per channel for FBGs (Figure 3a). Note that wavelength range is just one cost-sensitive parameter of the interrogator among many others, including wavelength accuracy, wavelength repeatability, dynamic range, and acquisition frequency, etc. Some of these parameters, such as acquisition frequency, can also be downgraded for practical battery applications, since we may not need 1000 data points per second (one standard acquisition rate for interrogators) to overwhelm the data storage and processing. Alternatively, the wavelength division multiplexing (WDM, for example, by writing a few FBGs in one fiber or coupling a few single-FBG fibers via fiber couplers) or time division multiplexing (TDM, for example, by means of an optical switch to

surveil each sensor one after the other) enables the sharing of one interrogator by hundreds of FBG sensors, possibly bringing the interrogation cost for each sensor possibly down to 10^0 US$ scale (Figure 3b).

Another short-term strategy for lowering the cost is to keep the optical interrogator offline with the charging station for *in situ* diagnosis only so that one interrogator can be shared by numerous EVs (Figure 3c). The ultimate realization of operando battery sensing will rely on the development of low-cost interrogators (Figure 3d). While the low-cost fiber charge-coupled detector (CCD) interrogator[36] is an available option in the short term by compromising the resolution, the success of silicon photonic integration[37] will offer a compact, low-cost, and possibly high-resolution on-chip interrogator for the onboard sensing. In this direction for battery applications, PARC has already done some pioneering work by exploring the low-cost and compact interrogation readouts[35, 38]. Besides, interrogators in the size of a memory stick are also being developed[39].

In short, all the sensors offer different sensing capabilities. We thus expect that two or three different sensors will combine together to provide an encompassing tracking of batteries' life cycle. Among them, the electrochemical method will remain as the foundation, while we modestly suggest that versatile fiber optic sensors that are immune to electrical shock and electromagnetic interference are the future complements, provided that the costs of sensor and interrogation system are reduced by the cross-disciplinary engineering/scientific innovations together with the mass production.

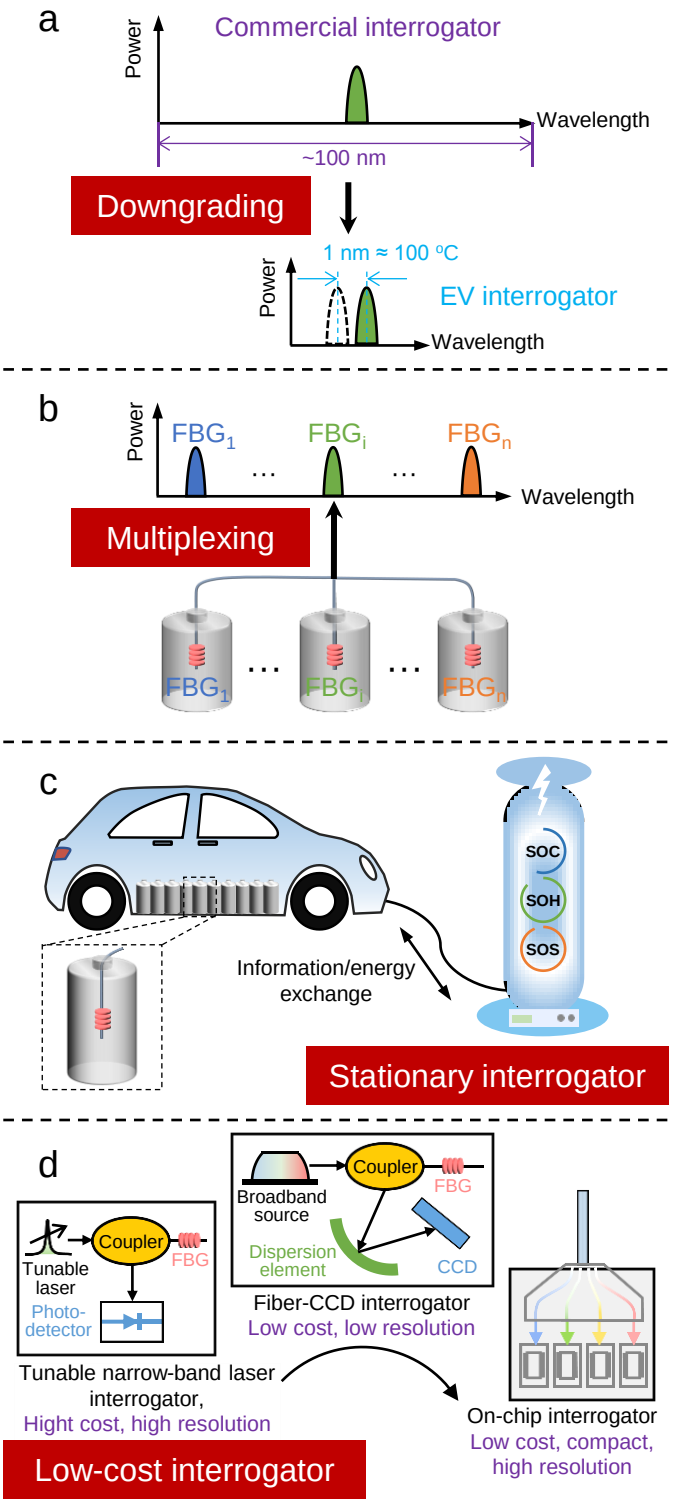


Figure 3 | Reducing the cost of interrogation. a, Downgrading the wavelength range of interrogator. **b,** Wavelength division multiplexing of multiple optical sensors in a single interrogation channel. **c,** Stationary interrogator for sharing the interrogation cost. **d,** Low-cost interrogators by fiber-CCD interrogator[36] and on-chip interrogator[37].

Implanting fiber optic sensors

If fiber optic sensors are selected from various battery sensors, the immediate question is how to exploit their added values by optimizing the positioning in batteries. The intuitive answer will be either the spatial mapping by a large number of sensing points or locating sensors at observables' (temperature, strain, etc.) maxima. The spatial mapping can be achieved by fully distributed (*e.g.*, Rayleigh)[12] or quasi-distributed (*e.g.*, FBG multiplexing) fiber optic sensing but at a relatively high cost. On the contrary, the key-point sensing, requiring much fewer sensor points and thus lower cost, seems closer to the practical applications. One controversy for key-point sensing is whether the fibers should be implanted into the cell, where the true maxima are located[7, 11]. In current cell designs, the ingress of fiber inevitably brings about invasiveness (though small due to the diameter of the fiber, <200 μm) and the extra sealing, pertaining to additional cost and risk of leakage. To escape from the invasiveness, the positioning of sensors on the surface of the cells may be the first step for commercializing fiber optic sensing technologies into batteries. However, maximizing the benefits of fiber optic sensing should ultimately be realized by implanting the sensors into the cells. We thus discuss the implanting positions and the sealing methods in different cell formats in Figure 4.

In cylindrical cells, the central voids of jelly rolls, that are formed during the fabrication, are ideal accommodations for optical fibers (Figure 4a); see our previous papers[7, 9, 12]. Particularly, the central positions are the hot spots of the cylindrical cells, as evidenced by the experiment[7]/simulation[11]. Free from strain, the FBG sensors hosted in the central voids can unambiguously sense temperature[7, 12] without cross-sensitivity issues. In conjunction with an additional FBG inscribed in microstructured optical fibers, hydraulic pressure resulting from the gas buildup can also be detected[7]. While using TFBGs in the central void, temperature, refractive index, and turbidity of the electrolyte can be decoupled by a single sensor[9]. To further sense the stress concentration, the fibers need to be implanted between jelly roll layers[35] or even embedded into the electrode[8, 25]. However, the ways to decouple the temperature and strain of FBG sensors should be further explored.

In pouch/prismatic cells with flat jelly rolls or stacking layers, the fiber sensors can be placed at the cell center between the layers[35] (Figure 4b), which is possibly the hot spot of the cell[40]. Similar to the cylindrical cells, the decoupling of temperature and strain can be complicated when implanting the sensors between layers. In the worst case, the coupled signal can still serve as a valuable input for battery management. Another interesting sensing position lies in ultrasonic or laser welded points between the tabs and positive/negative electrodes, where the interface/contact resistances may contribute to a hot pot[41]. On the other hand, a higher stress concentration is witnessed in the wound jelly roll structures than in the stacking ones[42], particularly at the corner (Figure 4b). Consequently, implanting one fiber sensor inside the wound corner may offer critical implications for the cell's mechanical degradation. However, we should be aware of the possibility that the implanting of the fiber sensor may aggravate the stress concentration, and the impact of implanting needs to be assessed and minimized carefully. In addition, the single cell can consist of multiple jelly rolls (see Apple's patent[43]). The sensors at the interface (Figure 4b) may monitor the interplay between jelly rolls.

After the implanting, the ports to inject the fibers should be closed by sealants (Figures 4c-e). In cylindrical cells (Figure 4c), epoxy sealants are adopted and show reliability under

mild conditions (55 ^{o}C or gassing) in lab scale[7, 9, 12]. However, epoxy may fail under EV operation conditions combining vibration, high/low temperatures, and gassing inside the batteries. Further testing and screening of sealants are thus necessary for the long-term reliability of the battery sensing. The same sealant can be used for prismatic cells, while the electrolyte filling port may simultaneously serve as the sensor injection port (Figure 4d). This, in turn, calls for the integrated design of sensors and cells with at least the pre-formed fiber ingress ports. The sensor sealing in the pouch cell may be much readier, because the protruding fiber is similar to the tabs and can be readily sealed with the assistance of heat seal film (Figure 4e) as reported by PARC[35]. Note that the optical signals can be collected by reflection and transmission modes[44], requiring one and two ports, respectively. One port and thus the reflection mode is indeed desired for fewer sealing points.

The emerging engineering designs, including cell to pack (CTP) and cell to chassis (CTC), may provide new opportunities for battery sensing. Note that the previous thermal sensors (*e.g.,* thermistors) are generally placed at the module level, and the elimination of the module in CTP may push the battery sensors to the cell level. BYD's gravimetrical CTP (GCTP) technology is based on the "blade" (characteristic of its thin but long dimension) battery (Figure 4f, left). The unique geometry of "blade" batteries may induce temperature gradients, and the implanting multiplexed sensors along the longitudinal direction can be interesting. While in CTC, the batteries become bi-functional, serving as both energy storage and structural components (Figure 4f, right). Recall that fiber optic sensors have been widely applied in structural health monitoring[24] in the construction sector, and thus bi-functioning of optical sensors for battery and structural sensing is readily feasible (Figure 4f, right). Aside from batteries, fiber optic sensors are increasingly explored for monitoring other components in EVs, such as tires[45]. Thus, a conjoined, versatile optic platform in EVs can be envisaged.

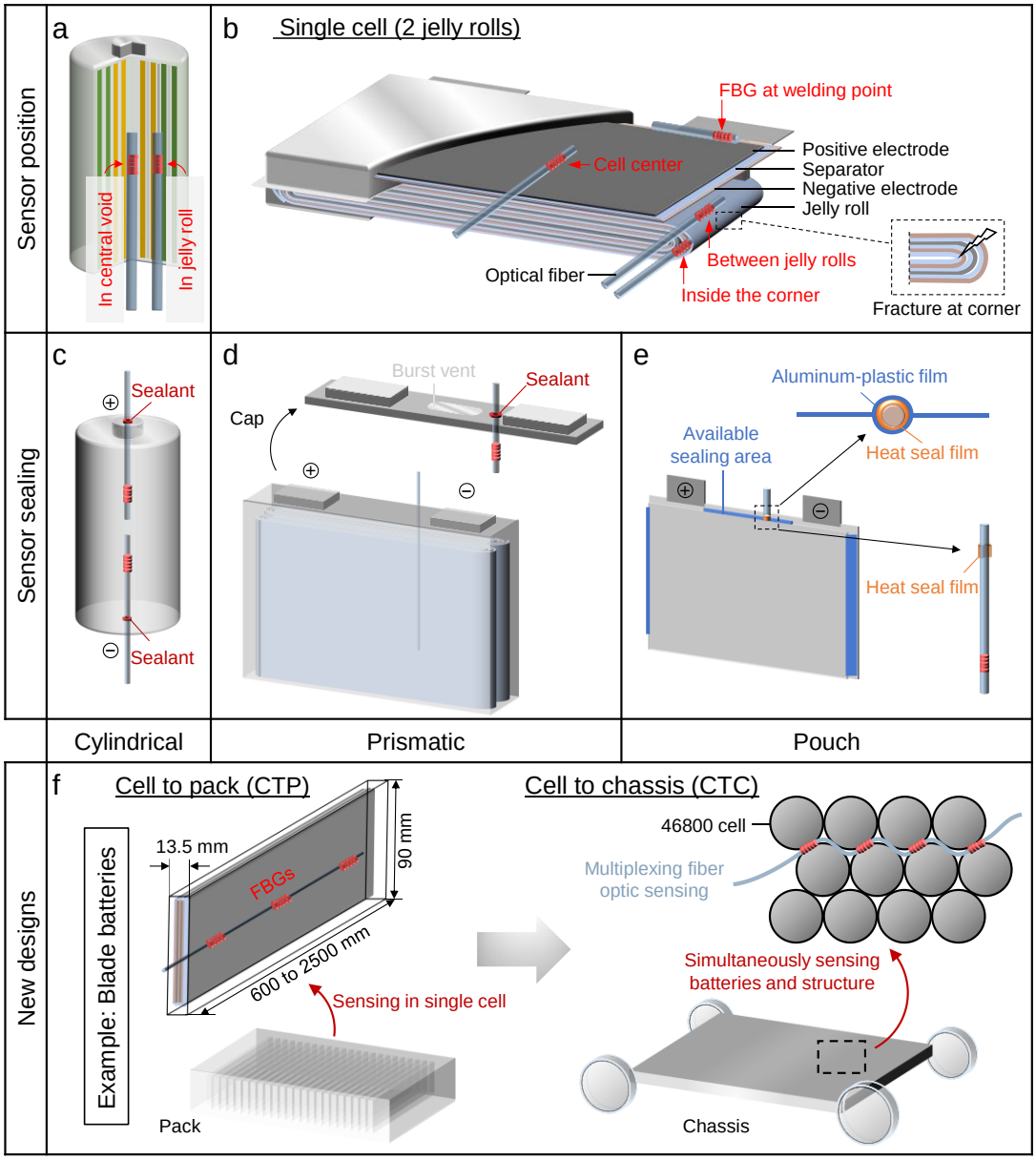


Figure 4 | Implanting fiber optic sensors. a,b, Sensor positions in cylindrical (**a**) and flat jelly rolls (**b**, taking a single cell with two jelly rolls as an example) for the pouch and prismatic cells. **c-e,** Sensor sealing in cylindrical (**c**), prismatic (**d**), and pouch (**e**) cells. **f**, Integrating optical sensor with new engineering designs, including cell to pack (CTP, left) and cell to chassis (CTC, right).

The monitoring of batteries at cell/system level by fiber optic sensors is exemplified in Figure 4. Thanks to the versatility of sensors, a multiscale operando monitoring of batteries is further envisioned (Figure 5). For example, at the electrode level, PARC has embedded the FBG sensors into the graphite electrodes of a pouch cell[25], while we have recently demonstrated the operando tracking of the stress evolution at the interfaces and electrodes of solid-state batteries[8]. Taking advantage of the evanescent field, we exploited the refractive index and turbidity of electrolyte[9] within the field (with a depth of 0.1-10 μm) at the particle level, and further investigated the chemical species (or functional groups) of electrolytes by the fiber infrared spectroscopy[1] at molecular level. Though promising, the simultaneous realization of multiscale monitoring is technically challenging, and we thus proposed the “lab-on-fiber”

solution[1, 9] recently.

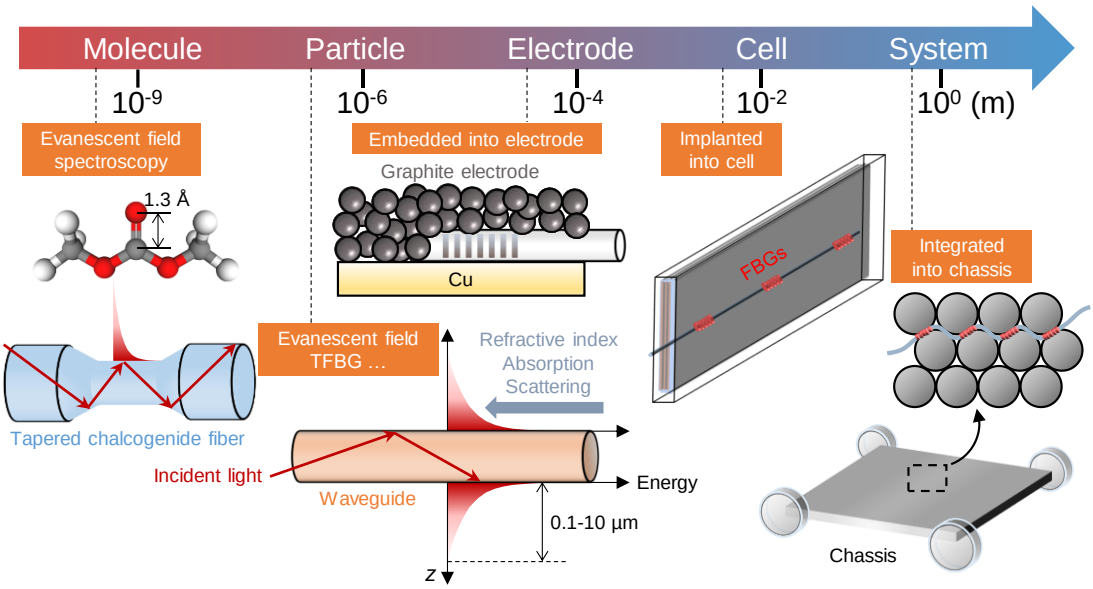


Figure 5 | Monitoring of batteries by fiber optic sensor at different length scales.

Outlook

In this Perspective, we demonstrate the opportunity and challenges of commercializing smarting sensing into batteries for a more sustainable, carbon-neutral world. Significant work remains to integrate the fibers, reduce the cost, and maximize the benefits of fiber optic sensors. In the short term, a demo battery pack consisting of optical sensors is desired to explore the wiring of fibers, the communication with battery management systems, and to quantify the added values of the optical sensors. In the long term, the fruitfulness of battery sensors will rely on the various actors from cross-disciplinary fields throughout both academia and industry.

Declaration of interests

A patent related to the work has been filed.

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