

**Mapping Out Commercial Gas Sensors to Measure Degradation Gases in  
Batteries**

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Master's thesis

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This research presents a comprehensive literature review on the use and possibilities of commercial gas sensors to detect and monitor degradation in batteries. Battery cells, especially under aging or fault conditions, emit various gases due to internal chemical decomposition. These gases have potential to serve as a key indicator of battery health, performance, and safety. Detecting such emissions can help in identifying degradation and potential failures, ultimately contributing to improved battery management and lifespan estimation.

The primary aim of this study is to evaluate gas sensor technologies capable of detecting emissions generated during battery degradation, including hydrogen, carbon monoxide, methane, and volatile organic compounds (VOCs). The focus is placed on sensors that can collect diagnostic information from within or near the battery cell, examining their operating principles, performance characteristics, and suitability for integration into battery monitoring, management, and control systems. The study particularly investigates electrochemical sensors, metal-oxide semiconductor (MOS) sensors, non-dispersive infrared (NDIR) sensors, and related technologies, assessing their capability to detect degradation-related gases and support early failure identification.

The research methodology involves a comparative analysis of various gas sensor technologies through an extensive review of both recent and historical scientific literature. Key sensor parameters evaluated include sensitivity, selectivity, response time, long-term durability, and commercial availability. The review also examines how these sensors quantify and characterize gas emissions, which in turn reflect the extent and progression of battery decomposition and degradation. This analysis provides a foundation for identifying sensor technologies most suitable for advanced battery diagnostic and safety applications.

Based on the literature review and comparative analysis, this study identifies several factors influencing sensor performance and reliability. It also outlines limitations that may lead to sensor failure or ineffective detection on critical gases. Through this evaluation, the thesis

provides informed recommendations for selecting the most effective gas sensors suitable for integration into battery research, development and control.

In conclusion, this study serves as a foundational reference for future experimental research, in using gas sensors as diagnostic tools for batteries particularly in addressing the state of health (SOH) of batteries. It also contributes to the advancement of sensor technology in the field of battery diagnostics and early fault detection.

**Key words:** Gas Evaluation in Batteries, Commercial Gas Sensors, Battery Management Systems BMS, Battery Degradation, Battery safety, Battery analytics.

## TIIVISTELMÄ

Tämä tutkielma on kirjallisuuskatsaus kaupallisten kaasusensoreiden käytöstä akkujen heikkenemisen havaitsemiseksi ja seuraamiseksi. Akkujen kennot, erityisesti ikääntyessään tai vioittuessaan, aiheuttavat kaasupäästöjä, jotka johtuvat kennojen sisällä olevien materiaalien hajoamisesta. Nämä kaasut voivat toimia ensisijaisena osoituksena akun kunnosta, suorituskyvystä ja turvallisuudesta ja niiden havaitseminen auttaa tunnistamaan akkujen kunnan heikkenemistä ja mahdollisia vikoja, mikä mahdollistaa paremman akkujen hallinnan ja elinkaaren arvioinnin.

Tämän tutkielman ensisijainen tavoite on arvioida kaasusensori teknologioita, joiden avulla pystytään havainnoimaan akkujen heikkenemisestä johtuvia kaasupäästöjä, mm. Hiilidioksidia, metaania ja haihtuvia orgaanisia yhdisteitä (VOC). Tutkielma keskittyy erityisesti akkukennoista tiedon keräämisen mahdollistaviin sensoreihin ja niiden toimintaperiaatteisiin, ominaisuuksiin sekä soveltuvuuteen osana akkujärjestelmiä. Tässä tutkielmassa tarkastellaan erityisesti sähkökemiallisia sensoreita, metallioksidisensoreita (MOS), epädispersiivisiä infrapuna sensoreita (NDIR), ja niihin liittyviä teknologioita ja arvioidaan sekä niiden kykyä havainnoida akkujen kuntoa.

Tutkimusmenetelmänä käytetään vertailevaa analyysia, jonka avulla vertaillaan eri kaasusensori teknologioita tarkastelemalla sekä viimeaikaisia että aiempia tieteellisiä artikkeleita ja julkaisuja. Kaasusensoreiden keskeisimmät tarkasteltavat ominaisuudet ovat mm. sensorien herkkyys, selektiivisyys, aikavaste, kestävyys ja kaupallinen saatavuus. Tutkimus painottaa kaasusensoreiden soveltuvuutta havainnoida kaasuja riippuen kaasun määrästä ja laadusta, mikä heijastuu akun kunnan heikkenemiseen ja materiaalien hajoamiseen.

Kirjallisuuskatsauksen ja vertailevan analyysin perusteella tämä tutkielma tunnistaa useita tekijöitä, jotka vaikuttavat sensoreiden suorituskykyyn ja luotettavuuteen. Lisäksi tutkielma tunnistaa rajoitteita, jotka voivat johtaa vikoihin sensoreissa tai kriittisten kaasujen tehottomaan tunnistukseen. Näiden arvioiden perusteella, tämä tutkielma esittää suosituksia tehokkaimmista sensoreista, jotka soveltuvat parhaiten käytettäväksi akkututkimuksessa.

Tämä tutkielma tarjoaa pohjan tuleville kokeellisille tutkimuksille, kaasusensorien käytöstä akkudiagnostiikassa erityisesti liittyen akkujen kuntoon. Lisäksi tämä tutkielma edistää sensorteknologian kehittämistä akkudiagnostiikan ja aikaisen vianmäärityksen osalta.

## Abbreviations

AI	Artificial Intelligence
BMS	Battery Management Systems
C-rate	Charge-Discharge rate
CNT	Carbon Nanotube
DOD	Depth of Discharge
EVs	Electric Vehicles
FBG	Fiber Bragg Grating
FPI	Fabry – Perot Interferometer
HF	Hydrogen Fluoride
IoT	Internet of Things
IR	Infrared
LiB	Lithium-ion Battery
LOD	Limit of Detection
MEMS	Microelectromechanical Systems
MOS	Metal Oxides Semiconductor Sensors
MPMS	Magnetic Property Measurement System
NDIR	Non-Dispersive Infrared Sensors
NIMH	Nickel – Metal Hydride
NTC	Negative Temperature Coefficient
OFDR	Optical Frequency Domain Reflectometry
PID	Photoionization Detectors
SEI	Solid Electrolyte Interphase

SOC	State of Charge
SOH	State of Health
SnO <sub>2</sub>	tin (IV) oxide
TDLAS	Tunable Diode Laser Absorption Spectroscopy
VOCs	Volatile Organic Compounds
ZnO	Zinc Oxide

### **Declaration**

I hereby declare that AI-based writing assistance tools have been used solely for the purpose of improving grammar, readability, and clarity of the text in this thesis. All technical ideas, concepts, contents, analyses, results, and interpretations are entirely my own. The AI-based tool were not used to generate original scientific content, data, or arguments but only to refine the written expression of my work.

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## 1 Introduction

As the global energy landscape transitions toward cleaner and more sustainable sources such as solar and wind power, efficient energy storage technologies have become increasingly vital. Batteries serve as the cornerstone of this transition by storing excess energy generated from intermittent renewable sources and delivering it when demand arises, thereby ensuring system stability and reliability [1]. In this context, battery safety and dependability are emerging as critical considerations for both researchers and industry stakeholders.

Batteries are now integral to nearly every aspect of modern life, powering portable electronic devices, electric vehicles (EVs), aerospace systems, and large-scale renewable energy storage installations. Among the various battery chemistries, lithium-ion (Li-ion) batteries have gained the most widespread adoption due to their high energy density, long cycle life, and their strong recharge performance. Their superior performance characteristics make them particularly suitable for applications requiring compactness, efficiency, and high-power output.

Despite these advantages, Li-ion batteries are susceptible to degradation and failure, which can pose significant safety risks. During degradation, a variety of gaseous byproducts such as hydrogen ( $H_2$ ), carbon monoxide (CO), and methane ( $CH_4$ ) can be released. These gases, many of which are categorized as volatile organic compounds (VOCs), serve as valuable indicators of the battery's internal health and degradation state [2]. However, it is important to note that hydrogen ( $H_2$ ) is not classified as a VOC. The detection and analysis of such gases provide critical insights into early-stage failure mechanisms, helping prevent hazardous events such as thermal runaway.

Commercial gas sensors have long been available; however, ongoing research is investigating whether this technology can be effectively applied to analyzing battery degradation gases. These sensors enable continuous monitoring of battery conditions, thereby improving system safety, reliability, and lifespan both now and in future applications. Accordingly, this study presents an overview of gas sensors and their functional role within battery systems, with particular attention to sensor types and their application in detecting gases generated during battery degradation.

## 2 Background and Challenges of In-Cell Gas Monitoring in Batteries

Gas monitoring within the interior of electrochemical energy storage devices remains technically challenging due to the complex and often subtle nature of gas evolution during battery operation. In lithium-ion and related battery chemistries, gas generation under normal cycling conditions is typically minimal and gradual. However, during abnormal operation such as ageing-induced degradation, side reactions, overcharge, or the initiation of thermal runaway, gas production can increase rapidly and unpredictably [1 - 3]. Identifying these changes at an early stage requires detection approaches with sufficiently high sensitivity and selectivity, particularly given the low concentrations of multiple gas species involved.

Analytical techniques capable of identifying gaseous species, including mass spectrometry and gas chromatography, are widely used in laboratory studies of battery degradation mechanisms. Nevertheless, these techniques are inherently external or ex-situ, as they rely on gas extraction, venting, or dedicated sampling cells to enable analysis [3, 4]. While such approaches provide detailed compositional information, they are not directly compatible with sealed commercial battery formats and are unsuitable for continuous internal monitoring during normal operation [5]. This limitation highlights the gap between laboratory-scale gas analysis methods and practical in-cell monitoring solutions.

The integration of sensing elements directly inside a battery cell introduces additional material, electrical, and mechanical constraints. Embedded sensors must operate reliably within the chemically aggressive electrolyte environment while tolerating potential gradients, temperature fluctuations, and repeated mechanical stress during cycling [5, 6]. At the same time, they must not influence electrochemical behaviour, compromise cell safety, or introduce risks such as internal short circuits or leakage. These stringent requirements significantly restrict the range of sensor materials and architectures that can be deployed inside active cells [6, 7].

As a consequence of these challenges, most existing approaches to gas-related monitoring rely on indirect indicators rather than direct measurement of gas composition within the sealed electrode stack. Commonly used proxies include internal pressure measurements, cell swelling or strain monitoring, and optical or acoustic techniques applied externally to the cell [5, 7]. While these methods provide valuable insight into abnormal operating conditions, the realization of a truly embedded sensor capable of selectively monitoring gas species within the active cell volume remains an open research challenge.

## 2.1 Research Questions

To guide this study, the following research questions have been formulated to explore the capabilities and practical applications of commercial gas sensors in monitoring battery degradation

- 1) Which commercial gas sensors can detect battery degradation gases? This inquiry investigates where and what type of sensors could measure and detects the degradation in batteries.
- 2) How can commercial gas sensor data be integrated into battery management systems to improve battery safety and longevity? This inquiry investigates the possibility of incorporating sensor data into monitoring systems, which could improve proactive battery management and prevent failures.
- 3) How do environmental conditions affect the effectiveness of commercial gas sensors used to measure the gases produced by decaying batteries? This question investigates the impact of conditions such as temperature and humidity on sensor accuracy and reliability in detecting degradation gases, crucial for real-world applications.

## 2.2 Role of Gas Sensor in Battery System Monitoring and Safety

Gas sensors play a vital role in identifying and quantifying gaseous species present in an environment. By converting gas concentration levels into corresponding electrical signals, these sensors enable the assessment of battery deterioration within energy storage systems and packs, which is increasingly demonstrated in current research and emerging practical implementations [3, 4]. This technology is widely applied across multiple domains, including air-quality monitoring, industrial safety, and energy storage management. Through the provision of real-time data, gas sensors support informed decision-making, mitigating potential risks and enhancing both operational safety and environmental protection. Consequently, gas sensing has become an essential tool for the early identification of faults, predictive maintenance, and failure prevention in advanced battery systems [3]. By detecting abnormal gas emissions, operators can identify probable faults before they escalate into catastrophic events.

A gas sensor operates by transforming a chemical interaction between target gases and a sensing material into a measurable electrical signal [4]. In battery monitoring applications, gas sensors serve several critical functions. The detection mechanism involves the interaction of target gases such as hydrogen ( $H_2$ ), carbon dioxide ( $CO_2$ ), and methane ( $CH_4$ ) with the sensing element, resulting in measurable changes in electrical properties such as resistance, current, or light absorption, depending on the sensor type [4]. This is followed by data interpretation, where the sensor transmits its electrical response to the battery management system (BMS), enabling automated safety actions when hazardous gas concentrations are detected.

These sensors have proven particularly valuable in both lithium-ion (Li-ion) and lead-acid battery technologies, where gas emissions act as early indicators of chemical degradation, electrolyte breakdown, or internal failure mechanisms [5]. As such, integrating gas-sensing technologies into battery management frameworks significantly enhances diagnostic accuracy, ensuring timely detection of anomalies and improving the overall safety, reliability, and lifespan of energy storage systems.

### 3 Battery Technologies

Common battery technologies, such as lithium-ion (Li-ion) as illustrated in Figure 1, lead-acid, nickel–metal hydride (NiMH), and emerging solid-state batteries each possess distinct characteristics that influence their performance and degradation behavior. Li-ion batteries, widely used in electric vehicles, consumer electronics, and grid storage systems, offer high energy density and long cycle life [6, 25]. Lead-acid batteries, though low in energy density, remain cost-effective and well established for starter and backup applications. NiMH batteries, commonly employed in hybrid vehicles, provide moderate energy density, while solid-state batteries, which utilize solid electrolytes, are being actively developed to improve safety and extend battery lifespan [25, 26].

Batteries gradually lose their ability to store energy over time, a process known as deterioration. This degradation can result from various factors, including electrode cracking, the formation of undesirable chemical layers, lithium plating on the anode, electrolyte decomposition, and gas generation within the cell [6, 25, 26]. Monitoring a battery's state of health (SoH) is therefore critical [25]. Without proper monitoring, accumulated gases and increased internal pressure can create safety hazards, potentially leading to fires or explosions [6, 7]. Performance also declines, reducing the range of electric vehicles and shortening the lifespan of backup batteries. Additionally, costs may rise due to premature replacement, and recycling or reuse becomes more challenging. Accurate knowledge of battery health enables the repurposing of used EV batteries for stationary storage in homes or industrial applications [25]. Overall, battery health monitoring is essential not only for safety but also for economic efficiency and environmental sustainability [7].

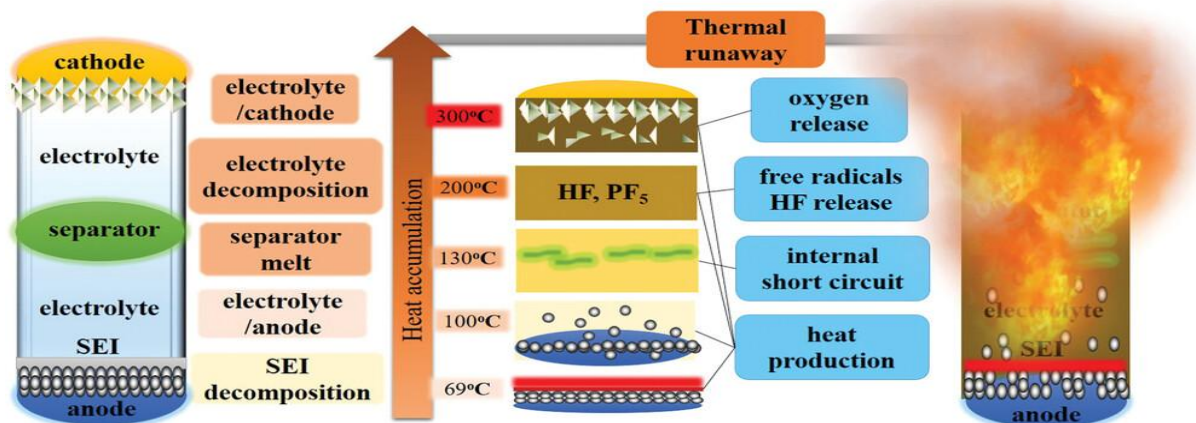


Figure 1. Evaluation Mechanism in Lithium-Ion Battery (LIB) [2].

### 3.1 Battery Degradation Monitoring

As illustrated in Figure 2, the early detection of failing automotive batteries can be achieved by monitoring the gases emitted during different stages of battery degradation. When batteries deteriorate, they often release specific gaseous by-products, summarized in 4.2. Table 2, which serve as early indicators of internal chemical and thermal processes. For instance, electrolyte decomposition generates hydrocarbons such as methane ( $\text{CH}_4$ ) and ethylene ( $\text{C}_2\text{H}_4$ ), while overcharging and lithium plating lead to the evolution of hydrogen ( $\text{H}_2$ ) and carbon monoxide ( $\text{CO}$ ). In more severe cases, overheating and subsequent thermal runaway produce gases such as carbon dioxide ( $\text{CO}_2$ ) and hydrogen fluoride ( $\text{HF}$ ) [4].

Gas sensors have therefore emerged as valuable tools for real-time battery health monitoring. By rapidly detecting these characteristic emissions, they can provide early warning signals of abnormal conditions within the cell, allowing corrective action to be taken before critical failure occurs, as shown in Figure 2. As widely reported in the literature, the early identification of such issues can significantly reduce the likelihood of accidents and enhance system safety [4].

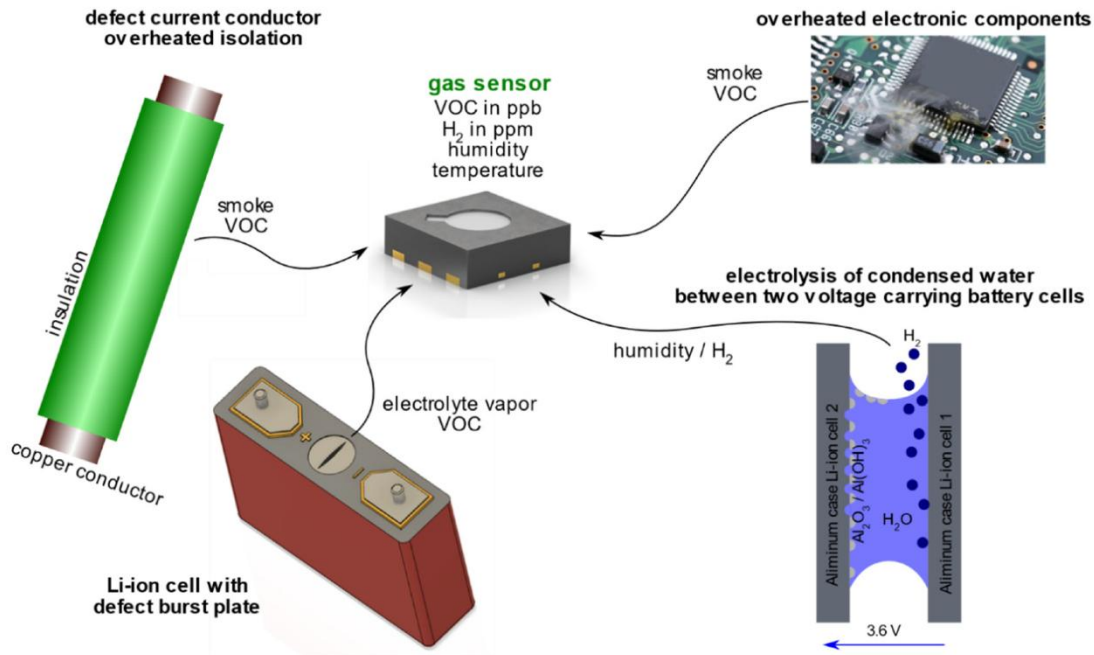


Figure 2. Monitoring Early Automotive Battery Degradation via Gas Sensors [8].

Gas sensors in batteries are used to detect early signs of electrolyte decomposition, such as volatile organic compounds like ethylene, as well as overcharge and lithium plating events, enabling the identification of potentially hazardous conditions before thermal runaway occurs. These gases are typically measured in the cell's headspace or within the battery enclosure, and in some cases may vent through safety valves. Furthermore, integrating gas sensors into battery management systems (BMS) enables safer operation by combining conventional electrical data (e.g., voltage and temperature) with chemical information from gas emissions [8].

### 3.2 Battery Degradation Mechanism

As illustrated in Figure 3, degradation mechanisms vary among battery types but generally encompass electrochemical, thermal, and mechanical processes. In Li-ion systems, electrochemical deterioration and the formation of the solid electrolyte interphase (SEI) lead to lithium inventory loss, electrolyte decomposition, gas evolution, and increased internal resistance. Repeated charge–discharge cycling induces mechanical degradation and electrode particle fracture, while high operating temperatures accelerate side reactions and electrolyte breakdown. At low temperatures, lithium plating further contributes to capacity fading. In lead-

acid batteries, sulfation, grid corrosion, and water loss are predominant degradation pathways [27,39].

Over time, both physical and chemical degradation in lithium-ion batteries manifest through uncontrolled side reactions, dendrite formation, and the loss of active lithium and electrolyte components. These processes reduce efficiency, capacity, and safety, and may trigger internal short circuits or thermal runaway [9]. Several operational parameters, including charge–discharge rate (C-rate), depth of discharge (DoD), temperature, and storage duration, strongly influence degradation kinetics. Elevated temperatures and deep discharges accelerate aging, while mechanical stress within electrodes exacerbates material fatigue. Consequently, battery management systems (BMS) play a vital role in monitoring voltage, current, and temperature to prevent hazardous conditions and prolong service life [17,30].

Degradation factors can be broadly categorized as electrochemical overcharge, over-discharge, current density, cycling rate, thermal (elevated temperature, non-uniform heat distribution, and structural material defects, electrode morphology, or impurities) [9,31]. These processes collectively impact capacity retention, power output, safety, and overall longevity, often leading to performance loss or thermal instability [10]. To ensure safety and reliability, continuous monitoring using BMS supplemented by advanced diagnostic tools such as electrochemical impedance spectroscopy (EIS), temperature sensing, and predictive algorithms is essential [11]. Furthermore, gas sensors are increasingly integrated into battery systems to enable real-time monitoring of critical safety and environmental indicators [1]. Building on this understanding of degradation mechanisms, the following section presents a focused example on solid-state batteries, illustrating how degradation manifests in this next-generation technology and how these insights can guide improvements in design and monitoring strategies.

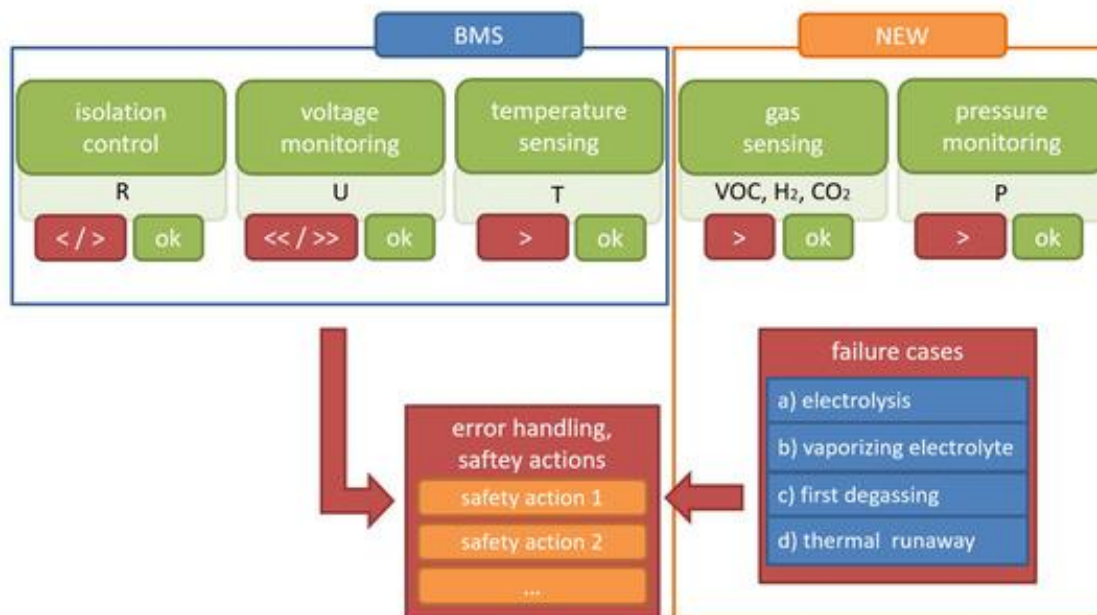


Figure 3. Gas Sensor-Based Detection of Early Battery Degradation [8].

The proposed extended concept of early detection of battery problems is highlighted in orange in the figure above and labeled "NEW".

### 3.3 Solid State Battery

Solid-state batteries (SSBs) represent a major advancement in energy storage technology by replacing the flammable liquid electrolytes used in conventional lithium-ion batteries with solid ceramic or polymer electrolytes. This design enhances safety because solid electrolytes are non-flammable, while enabling the use of lithium metal anodes that substantially increase energy density [57, 58, 67, 68].

Despite these advantages, SSBs still undergo degradation driven by multiple interrelated mechanisms [12]. One critical pathway involves interfacial reactions at the lithium metal–solid electrolyte boundary particularly in sulfide- and oxide-based systems. These reactions can form resistive interphases such as  $\text{Li}_2\text{S}$  or  $\text{Li}_3\text{P}$ , increasing internal resistance and hindering ionic transport. Mechanical failure and dendrite penetration further compromise performance: repeated lithium plating and stripping induce stress and micro-cracking within the electrolyte, facilitating dendrite growth and potential internal short circuits. Instability at the cathode–electrolyte interface also presents challenges, as high-voltage cathodes may oxidize sulfide electrolytes, forming insulating species that reduce capacity and cycle life. Together, these

degradation modes including interfacial reactions, mechanical damage, dendrite growth, and chemical instability drive resistance buildup, diminished ionic conductivity, and eventual failure [13].

Although SSBs lack liquid electrolytes, gas evolution can still occur under extreme conditions such as elevated temperature, high voltage, or overcharging. Electrolyte decomposition under these stresses may generate gases including sulfur dioxide (SO<sub>2</sub>), hydrogen sulfide (H<sub>2</sub>S), carbon dioxide (CO<sub>2</sub>), and oxygen (O<sub>2</sub>). Accumulation of such species can increase internal pressure, promote delamination at electrode–electrolyte interfaces, or signal internal failure. Experiments show that Ni-rich cathodes paired with sulfide electrolytes can emit measurable quantities of gas during aggressive cycling, directly linking electrochemical degradation to gas release [14].

Because gaseous byproducts reflect internal chemical and electrochemical changes, gas detection offers a valuable diagnostic method for assessing SSB health and stability. Metal-oxide semiconductor (MOS) sensors and electrochemical detectors can identify trace levels of H<sub>2</sub>S, CO<sub>2</sub>, and other gases in real time, while advanced analytical tools such as online electrochemical mass spectrometry (OEMS) and photoacoustic spectroscopy enable precise correlations between gas evolution and specific electrochemical events. Such monitoring supports early detection of interfacial breakdown, thermal instability, and other failure precursors, thereby enhancing safety and supporting lifetime prediction. The integration of gas-sensing technologies into SSB systems thus represents a promising direction for improving reliability, safety diagnostics, and overall performance [15].

In summary, SSBs offer substantial gains in safety and energy density, yet remain susceptible to degradation processes that can also produce gaseous byproducts. Monitoring gases such as H<sub>2</sub>S, SO<sub>2</sub>, CO<sub>2</sub>, and O<sub>2</sub> provides critical insight into decomposition reactions and failure mechanisms. Incorporating gas-sensing platforms from MOS and electrochemical sensors to spectroscopic systems enables non-invasive, real-time diagnostics that support safer operation and more accurate lifetime assessment, underscoring the growing importance of gas-evolution studies in advancing next-generation solid-state battery technologies [16].

### 3.4 Battery Management Systems (BMS)

A Battery Management System (BMS) is a critical electronic subsystem responsible for the supervision, control, and protection of rechargeable battery packs in a wide range of applications, including electric vehicles, grid-scale energy storage, consumer electronics, and portable tools. Often described as the “brain” of the battery, the BMS plays a central role in ensuring safe operation, optimizing performance, and prolonging battery lifetime. To achieve this, the system continuously monitors key operational parameters such as individual cell voltages, total pack current, and temperature at multiple points within the battery pack. The acquisition of real-time data enables early detection of abnormal conditions and supports informed control decisions that maintain operation within safe limits [54 – 56].

One of the most essential functions of the BMS is protection against hazardous operating conditions. The system is designed to disconnect the battery or restrict operation when it detects over-voltage, under-voltage, over-current, or excessive temperature. For instance, during charging, if a cell voltage exceeds its prescribed maximum, the BMS intervenes to prevent overcharging, which could otherwise lead to accelerated degradation, thermal runaway, or fire. Similarly, during discharge, the system prevents cells from dropping below their minimum voltage threshold, thereby avoiding irreversible capacity loss. Over-current protection safeguards the battery against short circuits and abnormal load conditions, while over-temperature protection isolates the pack to prevent overheating and associated safety risks [57 - 58].

To further enhance performance and extend service life, the BMS manages charge balancing among individual cells. Due to inherent manufacturing tolerances and aging effects, cells within a battery pack may exhibit unequal charge and discharge behavior over time, leading to imbalance and reduced usable capacity. The BMS mitigates this issue through balancing strategies, which may be passive dissipating excess energy from higher-voltage cells as heat or active redistributing energy from stronger cells to weaker ones. In addition, many BMS implementations interface with thermal management subsystems, such as forced-air or liquid cooling, to maintain the battery within an optimal temperature range and reduce degradation mechanisms [54 – 56].

Another core responsibility of the BMS is state estimation and data reporting. The system computes the state of charge (SOC), representing the remaining usable energy, and the state of

health (SOH), which reflects the battery's aging condition relative to its initial capacity. These quantities are typically estimated using a combination of current integration, voltage-based correction, and model-based algorithms. Through communication interfaces such as the Controller Area Network (CAN) in automotive applications or the System Management Bus (SMBus) in portable electronics, the BMS transmits this information to higher-level control units, enabling intelligent energy management, diagnostics, and user feedback [57, 59].

In parallel with advances in battery technologies, gas detection systems have also evolved significantly, particularly through the integration of Negative Temperature Coefficient (NTC) thermistors. An NTC thermistor is a temperature-sensitive resistor whose resistance decreases with increasing temperature, allowing accurate and rapid temperature measurement. While NTC thermistors are not typically used as primary gas-sensing elements, they play an important supporting role in gas detection systems by enhancing measurement stability and reliability [17].

One such application is thermal conductivity detection (TCD), also referred to as katharometry, which exploits differences in the thermal conductivity of gases. In a typical TCD configuration, NTC thermistors are incorporated into a Wheatstone bridge circuit, with some elements exposed to a reference gas and others to the target gas. When electrically heated, the thermistors cool at rates determined by the surrounding gas's thermal conductivity. The resulting resistance imbalance generates a voltage signal proportional to gas concentration, making this technique suitable for detecting gases such as hydrogen, carbon dioxide, and methane [56].

Another critical function of NTC thermistors in gas detection systems is temperature compensation for primary sensing elements. Many gas sensors, including metal oxide semiconductor (MOX) and electrochemical sensors, exhibit temperature-dependent behavior that can introduce significant measurement errors under varying environmental conditions. By placing an NTC thermistor in close proximity to the main sensor, the system can measure ambient or sensor temperature and apply real-time compensation algorithms. This approach significantly improves measurement accuracy and stability across a wide operating temperature range [50, 56].

### 3.5 Quality Control in Battery Management

In manufacturing, gas-detection systems are routinely used for exhaust monitoring during battery production. They monitor the environment around cell assembly to detect unwanted gas emissions and volatile electrolyte vapors. For example, hydrogen-fluoride (HF) detectors are used during the formation stage to detect potential electrolyte leakage [18, 80].

In large-scale batteries often referred to as grid-scale energy storage integrated gas monitoring systems provide safety surveillance. The sensors typically are electrochemical types, capable of detecting gases such as hydrogen sulfide (H<sub>2</sub>S) and hydrogen (H<sub>2</sub>), which may be generated during charging of lead-acid or lithium-ion batteries [19, 82].

Manufacturers often combine various gas-detection technologies into unified systems, enabling comprehensive monitoring for different gas hazards at energy-storage facilities. This integrated approach simplifies safety management and improves effectiveness [20, 21].

### 3.6 Future Expectation in Battery Management

Advanced gas-sensing systems are expected to play a critical role in the future of battery management, enhancing state-of-charge (SOC) and state-of-health (SOH) monitoring by providing early warnings of battery degradation. By detecting minute quantities of gases emitted during normal or abnormal operation, these systems can alert users to potential thermal, mechanical, or chemical issues before they lead to failure [1]. In particular, trace gas monitoring has shown promise in detecting early signs of interfacial degradation processes in lithium-based systems. Semiconductor-based gas sensors with sub-ppm sensitivity are being actively developed for this purpose, offering potential for early detection of degradation phenomena [22].

In the development of solid-state batteries, high-sensitivity gas chromatography, such as that provided by Agilent Technologies, is used to characterize gas evolution during cycling. This approach aids in improving electrolyte stability and allows early diagnosis of gas-related degradation, supporting the advancement of safe and reliable solid-state battery technology.

Gas sensing is also emerging as a critical tool in battery recycling operations. Advanced optical gas sensors can be used to monitor emissions of hazardous substances, including mercury vapor and other toxic gases, during battery disassembly and material recovery processes. For hydrogen management, chargeable nickel–metal hydride (NiMH) batteries require monitoring systems capable of detecting hydrogen at low concentrations during charging to prevent explosive hazards. Catalytic and resistive gas sensors are commonly employed for this purpose due to their sensitivity and reliability [7].

Lithium-ion batteries, particularly those intended for aerospace applications, benefit from specialized photoionization detection (PID) systems developed by Airbus and NASA, capable of detecting multiple gas species at ppb levels [6]. For general lithium-ion battery safety, gas detection systems monitor volatile organic compounds (VOCs), hydrogen, and carbon monoxide during thermal events. NTC thermistors, provided by Amphenol Advanced Sensors, and HF detectors from MSA Safety are used for quality control and electrolyte leakage detection during production [7]. For grid-scale energy storage, integrated monitoring systems increasingly rely on gas sensing technologies, including electrochemical and non-dispersive infrared (NDIR) sensors, to detect degradation-related gases and enhance operational safety [23].

Battery applications are diverse, spanning consumer electronics (phones, laptops, wearables), electric vehicles (rapidly adopting lithium-ion batteries), grid storage for renewable energy backup, medical devices (pacemakers, insulin pumps), and aerospace/defense systems (military aircraft, naval vessels, and advanced weapons systems). In all these domains, future battery management strategies will increasingly rely on gas-sensing technologies to enhance safety, extend lifespan, and support proactive maintenance.

Increased transportation mobility, electric vehicle (EV) adoption, renewable resource integration, smart devices, and mobility technologies has expanded the scope of traditional batteries beyond gadgets [24].

## 4 Gas Sensor and Operating Principle

Gas sensors are analytical devices designed to detect the presence and concentration of gaseous species in a given environment. They are widely utilized in applications such as safety monitoring, industrial process control, and environmental assessment, and have recently gained importance in battery research for identifying gaseous degradation products generated during degradation processes in lithium-ion batteries [30]. These sensors operate by converting chemical interactions between target gases and sensing materials into measurable electrical signals, which are proportional to the gas concentration. Most gas sensors rely on the interaction of gas molecules with an active sensing surface, leading to detectable changes in current, voltage, or resistance [10].

Several types of gas sensors have been developed based on different detection mechanisms. Electrochemical sensors function by measuring the current generated from redox reactions occurring when the target gas interacts with an electrode; these are commonly employed for detecting gases such as oxygen ( $O_2$ ) and carbon monoxide (CO). Semiconductor (metal-oxide) sensors, typically utilizing materials such as tin oxide ( $SnO_2$ ) or zinc oxide (ZnO), detect gases through resistance changes in the sensing film upon adsorption of gas molecules, offering good sensitivity toward VOCs and CO. Infrared (non-dispersive infrared, NDIR) sensors identify gases by measuring the absorption of infrared light at specific wavelengths and are frequently used for carbon dioxide ( $CO_2$ ) detection. Catalytic bead sensors monitor temperature changes caused by oxidation of combustible gases on a catalyst surface, making them suitable for detecting flammable species. Finally, photoionization detectors (PIDs) employ ultraviolet (UV) light to ionize volatile organic compounds (VOCs) and measure the resulting current.

In all these sensor types, the measurable signal varies proportionally with gas concentration. For instance, in metal-oxide semiconductor sensors, oxygen adsorption on the surface captures free electrons, increasing resistance; when a reducing gas such as CO reacts with the adsorbed oxygen, electrons are released back to the conduction band, leading to a measurable decrease in resistance. Through such mechanisms, gas sensors provide real-time quantitative information on the composition of gaseous environments, contributing significantly to safety assurance, industrial monitoring, and the detection of degradation by-products in battery systems, where such gaseous species are associated with degradation and failure mechanisms [30].

#### 4.1 Comparative Evaluation of Gas Sensors Technologies based on Key Performance Characteristics

To evaluate the suitability of different gas sensing technologies for monitoring battery degradation, commonly used sensor types are compared based on key performance characteristics, including sensitivity, response time, selectivity, and power consumption [9,10,32]. Table 1 summarizes these characteristics and highlights the relative advantages and limitations of each technology in the context of battery monitoring applications.

Table 1. Major Gas Sensor Type and Technologies

Sensor Type	Sensitivity	Response Time	Selectivity	Power Consumption	Suitability for Battery Monitoring
Electrochemical	High (ppm level)	Moderate	High	Low	Best for portable battery safety applications
MOS	Moderate	Fast	Moderate	High	Good for real-time monitoring but power-hungry
Catalytic Bead	High (flammable gases)	Moderate	Moderate	High	Suitable for industrial-scale monitoring
IR	High for CO <sub>2</sub> and CH <sub>4</sub>	Slow	Very High	Low	Ideal for stationary large-scale battery systems

The suitability classifications presented in Table 1 are derived from the operational characteristics and limitations of each sensing technology reported in the literature, particularly in the context of lithium-ion battery gas detection and safety monitoring [8, 31, 32, 9, 26]. A wide range of gas-sensing technologies has been explored for monitoring battery degradation and failure, each offering specific operational characteristics and trade-offs in terms of sensitivity, selectivity, stability, response time, and power requirements. Semiconductor metal-oxide (MOS) sensors, which detect gases through resistance changes in materials such as SnO<sub>2</sub>,

ZnO, and TiO<sub>2</sub>, are among the most widely implemented due to their high sensitivity and rapid response to species commonly released during lithium-ion battery degradation, including H<sub>2</sub>, CH<sub>4</sub>, CO, CO<sub>2</sub>, O<sub>2</sub>, and various volatile organic compounds (VOCs) [31, 9]. Their detection mechanism, based on electron exchange during adsorption of reducing or oxidizing gases, makes them valuable for capturing early signatures of electrolyte decomposition and solid electrolyte interphase (SEI) breakdown. However, MOS sensors exhibit notable drawbacks: limited selectivity, susceptibility to humidity and temperature variations, long-term drift, and a high operating temperature requirement (typically 200–800 °C), which increases system complexity despite their low material cost [8].

Non-dispersive infrared (NDIR) sensors provide an alternative optical approach by sensing gas-specific absorption of infrared light, delivering excellent selectivity and long-term stability, especially for CO<sub>2</sub> and CH<sub>4</sub> two key indicators of thermal and chemical battery failure [32]. Their slower response times and higher cost, however, restrict their integration primarily to stationary or large-scale installations with fewer constraints on size, budget, and power. Catalytic bead sensors, which measure the heat generated during oxidation of combustible gases such as hydrogen and methane, offer high sensitivity in safety-critical environments but suffer from poor selectivity and high-power consumption, making them unsuitable for portable or embedded battery systems [26].

Electrochemical sensors present a contrasting profile: while not relying on thermal or optical transduction, they offer strong selectivity, ppm-level sensitivity, low power consumption, and moderate response times. These advantages position them as highly suitable for compact or battery-powered monitoring architectures. When the major performance metrics sensitivity, selectivity, response time, and stability are compared, electrochemical sensors consistently provide the most balanced properties for low-power applications, whereas MOS sensors deliver the fastest detection at the expense of cross-sensitivity and high energy demand. Catalytic sensors remain valuable for industrial hazard detection, and IR sensors excel in stability and selectivity but often at increased cost and slower response rates [32,8].

These trade-offs align with general performance criteria for gas sensors. Sensitivity, typically expressed in ppm or ppb, defines the minimum detectable concentration of battery off-gases; selectivity enables discrimination among gases such as CO, H<sub>2</sub>, CH<sub>4</sub>, and electrolyte vapors; response time governs the ability to detect hazardous conditions within seconds; and long-term stability determines resistance to drift, poisoning, and environmental aging [9,32]. Power consumption and acceptable operating temperature range are additional constraints of particular relevance for integration inside battery packs, where thermal and electrical budgets are limited.

Beyond established MOS, electrochemical, and infrared sensors, several emerging technologies aim to address limitations in selectivity, robustness, and energy efficiency. Optical and fiber-optic sensors, for instance, leverage molecular absorption features to achieve extremely high sensitivity and excellent selectivity with response times on the order of milliseconds to seconds. Despite their strong environmental stability, their high cost and complex integration requirements confine them primarily to laboratory diagnostics and high-end safety systems. Their performance characteristics as shown in Figure 4, are often illustrated in sensor-model simulations, such as those demonstrating temperature and pressure responses relevant to battery fault conditions.

Conducting polymer and carbon-nanotube (CNT) sensors provide moderate-to-high sensitivity with low power requirements because they operate near room temperature. However, their selectivity remains moderate, and they are prone to environmental effects such as humidity and long-term aging, which degrade stability [32,9]. Likewise, emerging self-powered and nanomaterial-based sensors capable of harvesting energy from vibrational or thermal gradients within a battery pack show promising sensitivity and response times but remain less mature and lack long-term reliability data [32,9].

Finally, sensor arrays enhanced with artificial-intelligence (AI) algorithms represent an advanced strategy for battery safety diagnostics. By combining signals from multiple sensing mechanisms, these “electronic nose” architectures compensate for individual sensor weaknesses, providing significantly improved selectivity, reduced false alarms, and enhanced predictive capability regarding battery health and failure modes. Despite higher initial cost and algorithmic complexity, they are increasingly regarded as long-term cost-effective solutions for comprehensive, accurate, and proactive battery monitoring.

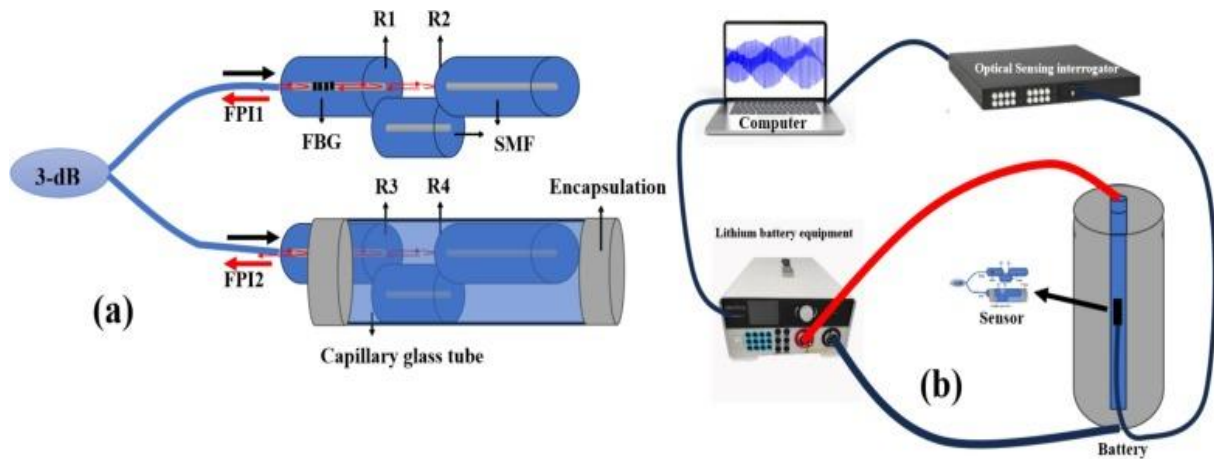


Figure 4. Stimulation Measurement of Temperature and Pressure of Sensor Model [34]. Diagram of sensor model and test scheme. (a) Diagram of sensor model; (b) Diagram of test scheme.

## 4.2 Gaseous Byproducts Generated During Battery Degradation Processes

Gaseous byproducts generated during battery degradation serve as important indicators of aging mechanisms and potential safety hazards. Electrochemical, thermal, and chemical degradation processes within the cell can lead to the release of various gases, depending on the operating conditions and materials involved [11]. The gaseous byproducts listed in Table 2 and their associated formation mechanisms are well documented in the literature on lithium-ion battery degradation and thermal runaway processes.

Table 2. Gases Generated During the Degradation [11].

Gas	Source of Production	Potential Risk
Hydrogen (H <sub>2</sub> )	Generated from electrolyte decomposition or reactions between lithium and metal oxides during overcharge or thermal abuse.	Highly flammable; poses explosion risk in confined environments.
Carbon Dioxide (CO <sub>2</sub> )	Produced from the decomposition of organic carbonate solvents and breakdown of the solid electrolyte interphase (SEI).	Can displace oxygen in enclosed spaces; contributes to pressure buildup.

<b>Gas</b>	<b>Source of Production</b>	<b>Potential Risk</b>
Carbon Monoxide (CO)	Formed through incomplete oxidation of electrolyte components and carbonates under high temperature or voltage.	Highly toxic; flammable and forms explosive mixtures with air under elevated concentrations.
Methane (CH <sub>4</sub> )	Arises from thermal or electrochemical decomposition of electrolyte solvents at elevated temperatures.	Flammable; Flammable; forms explosive mixtures with air
Oxygen (O <sub>2</sub> )	Released from cathode materials (e.g., LiCoO <sub>2</sub> ) during overcharge or thermal runaway.	Supports combustion; accelerates fire and thermal runaway.
Volatile Organic Compounds (VOCs)	Generated from degradation of electrolyte additives and polymer binders.	Toxic; may form secondary hazardous gases upon oxidation.

Lithium-ion (Li-ion) batteries are known to emit various gaseous byproduct during operation, and failure. These gases primarily originate from electrolyte decomposition, electrode reactions, and thermal instability. Among the most frequently detected gases are hydrogen (H<sub>2</sub>), carbon dioxide (CO<sub>2</sub>), carbon monoxide (CO), methane (CH<sub>4</sub>), oxygen (O<sub>2</sub>), and volatile organic compounds (VOCs) such as ethylene and dimethyl carbonate [11].

The generation of these gases is closely associated with specific degradation mechanisms. Oxygen (O<sub>2</sub>) is typically released from the decomposition of cathode materials such as lithium cobalt oxide (LiCoO<sub>2</sub>). Carbon dioxide (CO<sub>2</sub>) is produced from electrolyte breakdown or overcharging, while hydrogen (H<sub>2</sub>) forms through electrolyte decomposition and anode reactions. Carbon monoxide (CO) results from incomplete decomposition of electrolyte solvents, and VOCs are generated from the degradation of organic electrolyte components. Tracking the evolution of these gases provides early warning indicators of thermal runaway or overall battery degradation [11]. The major gases produced during Li-ion battery degradation are summarized in Table 2.

Monitoring these gaseous emissions offers valuable insight into the internal condition and safety of Li-ion batteries. Gas formation not only reflects electrochemical or thermal degradation mechanisms but also represents significant safety concerns. Hydrogen and methane

are highly flammable, oxygen release can intensify combustion, and both carbon monoxide and VOCs pose toxicological hazards. Therefore, identifying and quantifying these gases at an early stage is critical for understanding battery health, improving safety, and preventing catastrophic failures.

To address these challenges, various gas-sensing technologies have been developed and integrated into modern battery management systems. Sensor types such as electrochemical, semiconductor, infrared, and catalytic devices have been utilized to detect key gases, including hydrogen, carbon monoxide, methane, and VOCs. The incorporation of such sensors enables real-time monitoring of gas emissions, allowing for early detection of faults, prevention of hazardous incidents, and extension of battery lifespan [6, 7, 25].

Future advancements in gas-sensing technology are expected to focus on enhanced selectivity, miniaturization, and integration with Internet of Things (IoT)-based monitoring platforms [25, 55]. These developments will contribute to improved reliability, safety, and performance of next-generation Li-ion battery systems.

## 5 Fundamentals Gas Sensor in Battery System

As temperature within a battery cell increases, decomposition of the electrolyte and the solid electrolyte interphase (SEI) leads to the generation of volatile organic species as well as CO and CO<sub>2</sub>, with gas evolution accelerating markedly under severe conditions above approximately 150–200 °C. Importantly, these gases can be released well before the onset or completion of thermal runaway. Distinct electrochemical and thermal processes at the anode and cathode such as oxygen release from high-nickel cathode materials or solvent reduction reactions at the anode produce characteristic gas signatures, including H<sub>2</sub>, CO, and CO<sub>2</sub>, which can be leveraged to identify specific failure modes [52]. In this context, both the time evolution and rate of gas generation are critical diagnostic parameters: a slowly increasing gas concentration or pressure baseline is typically indicative of aging-related degradation, whereas a rapid rise in gas concentration, hydrogen evolution, or internal pressure signals a potential catastrophic failure event. In certain failure scenarios, gas sensing can provide earlier warning than pressure-based detection, as trace levels of H<sub>2</sub> may be detectable prior to a measurable pressure increase. Moreover, gas sensing can be implemented at the cell-internal level, enabling direct detection of early degradation phenomena.

Gaseous species such as H<sub>2</sub>, CO, CO<sub>2</sub>, hydrocarbon fragments, HF, and other volatile organic compounds serve as early indicators of cell deterioration and precursors to thermal runaway in lithium-ion and related battery chemistries [16]. These gases arise from chemical and thermal decomposition of electrodes, electrolyte, and separator materials during abuse conditions, aging, or overcharge, as illustrated in Figure 5 [52]. While gas sensing provides valuable insight into degradation mechanisms, temperature and pressure remain the most direct and immediate indicators of abnormal operating conditions: temperature measurements reflect localized heat generation and hotspot formation, whereas pressure monitoring whether at the cell or pack headspace level or through detection of sudden pressure spikes indicates gassing, venting, or rapid decomposition processes. One specific application that illustrates the challenges of gas detection is the measurement of hydrogen fluoride (HF), a highly toxic and corrosive gas.

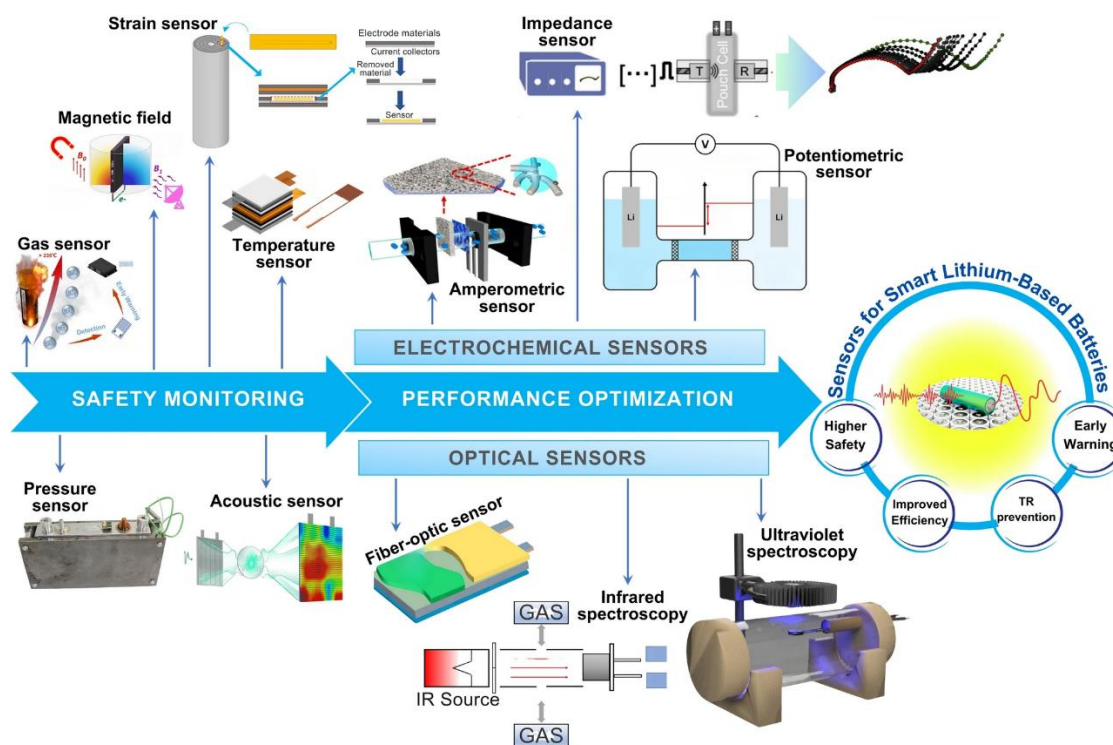


Figure 5. Sensor-Based Indicators of Degradation and Failure Mechanisms in Lithium-Ion Batteries LiB. [25].

HF detection requires sensors that are not only highly sensitive to detect low, hazardous concentrations, but also resistant to chemical degradation. The most common method for detecting HF is through electrochemical sensors, which contain a liquid electrolyte and a system of electrodes. HF gas diffuses into the sensor, dissolves in the electrolyte, and undergoes an electrochemical reaction that generates a current proportional to its concentration. These sensors are relatively low-cost, energy-efficient, and sensitive, but they are limited by a finite lifespan, potential electrolyte drying, and cross-sensitivity to other gases.

Advanced optical methods such as Tunable Diode Laser Absorption Spectroscopy (TDLAS) provide a highly selective and accurate approach to HF detection. TDLAS operates on the principle that each gas absorbs light at specific wavelengths. A laser tuned to the absorption wavelength of HF passes through the gas sample, and any reduction in light intensity is measured to determine gas concentration using the Beer–Lambert Law. This technique offers extremely high sensitivity, fast response times, and no cross-interference, but it requires expensive and complex instrumentation, making it more suitable for industrial or research environments [53].

Metal oxide (MOX) sensors present another option for HF detection, relying on changes in the electrical resistance of a heated metal oxide surface when HF molecules interact with it. These

sensors are inexpensive and long-lasting but typically suffer from poor selectivity and environmental sensitivity, particularly to humidity and temperature changes.

Together, the integration of systems like BMS in battery technologies and thermistor-based sensing reflects the broader trend toward smarter, safer, and more efficient energy and environmental management systems. As technological demands increase, these systems will continue to evolve, leveraging advances in materials science, electronics, and data processing to meet the challenges of modern applications [51].

### **5.1 Gas Sensing Mechanism of Pd-Doped rGO/ZnO–SnO<sub>2</sub> Hydrogen Sensor (Case Study)**

Gas sensing mechanisms in metal oxide semiconductors generally rely on surface adsorption and redox reactions between gas molecules and adsorbed oxygen species. In this section, a Pd-doped rGO/ZnO–SnO<sub>2</sub> sensor is presented as a representative case study to illustrate these mechanisms in hydrogen detection. This particular system is selected due to its combined advantages of high surface area (rGO), heterojunction effects (ZnO–SnO<sub>2</sub>), and catalytic enhancement (Pd nanoparticles), which make it highly relevant for advanced hydrogen sensing applications [5]. It should be noted that this type of sensor is primarily at the research and development stage and is not yet widely commercialized, but it reflects state-of-the-art design strategies in gas sensor technology.

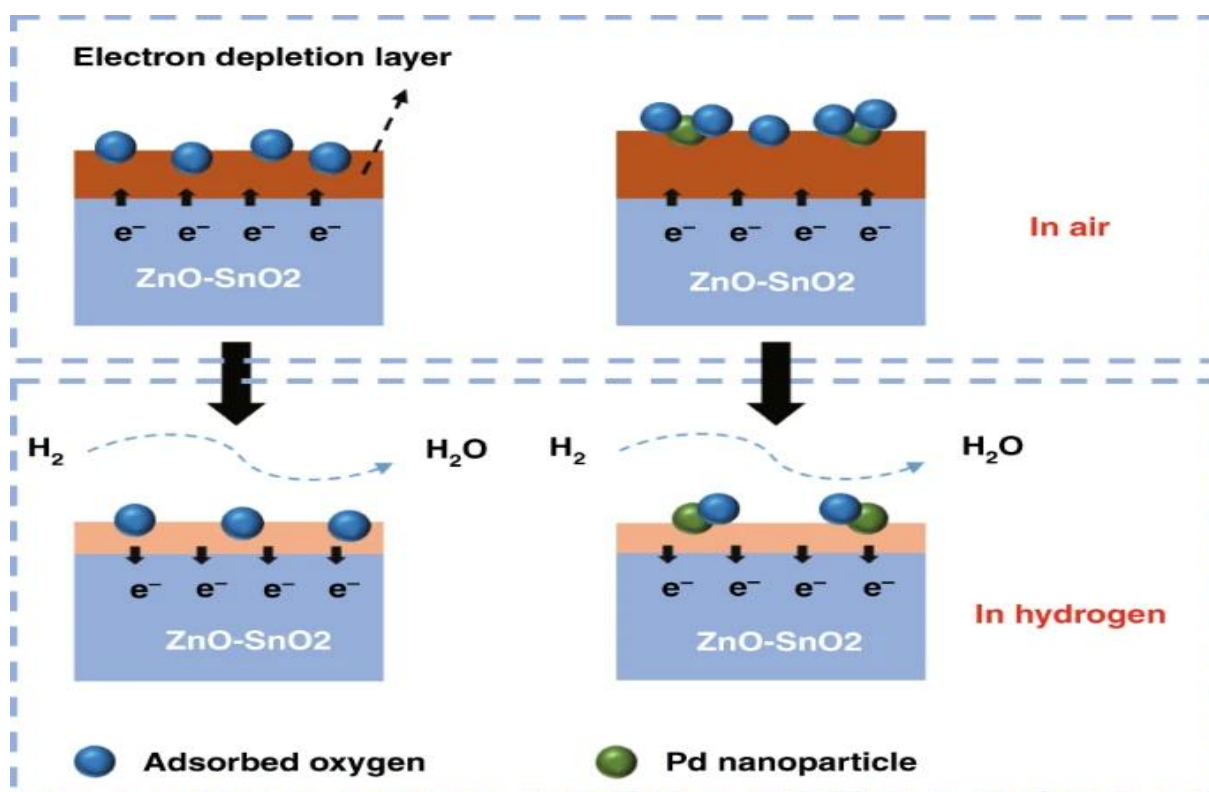
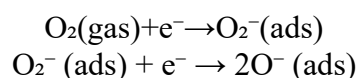


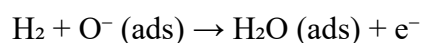
Figure 6. Gas Sensing Mechanism Action Diagram of Pd nanoparticles [26].

The gas sensing behavior of ZnO–SnO<sub>2</sub> nanocomposites is governed primarily by surface adsorption and redox reactions between gas molecules and adsorbed oxygen species. As illustrated in Figure 6, when the sensor is exposed to air (oxidizing environment), oxygen molecules (O<sub>2</sub>) are adsorbed onto the ZnO–SnO<sub>2</sub> surface and capture free electrons from the conduction band of the semiconductor according to the following reactions:



This electron withdrawal leads to the formation of an electron depletion layer (EDL) near the surface, which increases the overall resistance of the sensing layer due to the reduced electron concentration in the conduction band. The thickness of this depletion layer directly influences the sensor resistance under ambient air conditions [27].

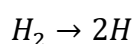
When the sensor is exposed to a reducing gas such as hydrogen (H<sub>2</sub>), hydrogen molecules diffuse onto the surface and react with the adsorbed oxygen species, producing water and releasing electrons back into the conduction band:



This reaction decreases the thickness of the EDL, thus reducing the sensor resistance. The change in resistance serves as a measurable indicator of hydrogen concentration, enabling sensitive and selective gas detection [27].

### 5.1.1 Catalytic and Electronic Role of Pd Nanoparticle in ZnO–SnO<sub>2</sub>-Based Hydrogen Sensors

The incorporation of palladium (Pd) nanoparticles significantly enhances the hydrogen sensing performance of ZnO–SnO<sub>2</sub> gas sensor systems due to their excellent catalytic and electronic properties. Pd possesses a strong affinity for hydrogen, allowing it to efficiently adsorb and dissociate hydrogen molecules even at low temperatures via:



This process, often referred to as the spillover effect, enables the dissociated hydrogen atoms to migrate from Pd sites to the ZnO–SnO<sub>2</sub> sensing surface, thereby accelerating reactions with adsorbed oxygen species. Moreover, Pd nanoparticles lower the activation energy required for hydrogen oxidation, promoting faster response and recovery times as well as enhanced sensitivity and selectivity toward hydrogen gas [57].

From an electronic perspective, Pd forms Schottky junctions with ZnO–SnO<sub>2</sub>, modifying local band structures and facilitating efficient electron transfer at the interface. Consequently, Pd nanoparticles act in a dual role catalytically (promoting hydrogen dissociation and reaction) and electronically (modulating surface charge dynamics) which collectively amplify the resistance change upon hydrogen exposure [28].

### 5.1.2 Application of Pd–ZnO–SnO<sub>2</sub> Gas Sensors in Hydrogen Leak Detection and Sensor State-of-Health Monitoring

Hydrogen is an odorless, colorless, and highly flammable gas, with an explosive concentration range in air of 4–75% [28]. Hence, reliable and rapid hydrogen detection is crucial for safety assurance [28]. Pd-doped ZnO–SnO<sub>2</sub> sensors offer real-time monitoring of hydrogen leaks by detecting changes in resistance as hydrogen concentration increases [28].

In long-term operation, the state of health (SOH) of the gas sensor itself becomes a critical factor [28]. Continuous exposure to reactive gases and thermal cycling can lead to degradation mechanisms such as Pd nanoparticle sintering, poisoning, or reduced oxygen adsorption activity [28]. These effects manifest as baseline drift (gradual change in resistance in air), diminished sensitivity (smaller resistance variation for the same gas concentration), and slower response/recovery kinetics [28].

Cross-sensitivity studies, involving exposure to interfering gases such as CO, CH<sub>4</sub>, and NH<sub>3</sub>, are essential to ensure selectivity and minimize false alarms, which is particularly important for industrial hydrogen safety systems [28]. Thus, Pd–ZnO–SnO<sub>2</sub> sensors not only detect hydrogen leaks but also provide diagnostic insights into sensor aging and performance degradation [28].

### 5.1.3 Practical Application of (Pd-ZnO-SnO<sub>2</sub>) Sensors

Pd–ZnO–SnO<sub>2</sub>-based sensors find practical applications in hydrogen-related technologies, including fuel-cell systems for leak detection, hydrogen storage and distribution infrastructure, and industrial hydrogen handling environments. In the context of battery systems, hydrogen evolution is often associated with degradation processes and can therefore serve as an indirect indicator of cell failure or safety risks.

The sensing behavior of Pd-doped ZnO–SnO<sub>2</sub> composites is generally attributed to surface adsorption and charge transfer processes. Under ambient conditions, oxygen species adsorb onto the sensor surface, leading to electron depletion and increased resistance. Upon exposure to hydrogen, surface reactions reduce the adsorbed oxygen species, resulting in electron release and a measurable change in conductivity. The incorporation of palladium enhances catalytic activity, promoting hydrogen dissociation and improving sensor response characteristics. While the fundamental sensing principles are well established in the literature, the relevance of hydrogen evolution as a degradation indicator is consistent with studies on failure mechanisms and gas generation in battery systems [10, 14].

Over time, degradation mechanisms such as material aging, surface contamination, or catalyst deactivation may affect sensor performance, leading to reduced sensitivity and slower response. Monitoring baseline resistance and response trends can therefore provide useful information regarding sensor stability and operational reliability. In battery-related environments, such

monitoring is particularly important, as gas evolution and associated performance degradation have been widely reported in electrochemical systems [10, 14].

## 5.2 Environmental Factors for Battery Safety Monitoring

A wide range of commercial sensing technologies is available for monitoring critical environmental and operational parameters in battery cells, modules, and packs. Each sensor type presents distinct advantages and limitations in terms of accuracy, cost, robustness, and suitability for specific applications. Among these, temperature sensing remains a fundamental requirement in both laboratory studies and field-deployed battery systems. Commonly used technologies include negative temperature coefficient (NTC) thermistors, resistance temperature detectors (RTDs), thermocouples, and fiber-optic Fiber Bragg Grating (FBG) sensors. NTC thermistors are widely employed in battery management systems (BMS) due to their low cost, compact form factor, and fast response. In contrast, RTDs provide higher accuracy and long-term stability, making them more suitable for laboratory validation and applications requiring precise thermal control. FBG sensors offer additional benefits, including immunity to electromagnetic interference (EMI), chemical inertness, and the ability to simultaneously measure strain and temperature, which makes them particularly attractive for advanced research and embedded sensing applications [61].

Pressure sensing is another important component of battery safety monitoring, as it enables detection of abnormal swelling, gas generation, and enclosure overpressure at both cell and pack levels. Typical solutions include microelectromechanical systems (MEMS) absolute and gauge pressure sensors, as well as dedicated battery-pack pressure monitoring sensors (BPMS) with integrated diagnostic functionality. These devices are designed for continuous operation with high reliability and minimal footprint, making them suitable for automotive and stationary energy storage applications. Commercially available implementations from major semiconductor and sensing manufacturers demonstrate the practical feasibility of such systems [84 - 86]. Monitoring pressure evolution within the enclosure allows early identification of venting behavior or mechanical failure prior to the onset of critical events.

Gas sensing has increasingly emerged as a key element in predictive battery safety monitoring, as it enables the detection of gaseous by-products released during the early stages of cell degradation. Among available technologies, non-dispersive infrared (NDIR) sensors offer high

selectivity and long-term stability for carbon dioxide (CO<sub>2</sub>) detection, making them well suited for monitoring battery enclosure atmospheres and identifying early venting phenomena. Commercial NDIR modules are widely documented in manufacturer datasheets and have been adopted in practical monitoring systems [87]. Metal-oxide semiconductor (MOS) sensors provide a cost-effective solution for detecting a broad range of volatile organic compounds (VOCs) and hydrocarbons; however, their limited selectivity and sensitivity to environmental conditions such as humidity and temperature must be carefully considered. Electrochemical sensors, on the other hand, offer high sensitivity and low power consumption, enabling detection of trace gases such as carbon monoxide and hydrogen sulfide at low concentration levels [16, 88].

More recently, MEMS-based hydrogen sensors have been specifically developed for battery safety applications, offering fast response times, low power consumption, and compatibility with BMS platforms. These sensors are particularly valuable because hydrogen is often released at an early stage of battery degradation, prior to full venting or thermal runaway. As such, hydrogen sensing provides an effective early warning mechanism for impending failure events [16, 89].

In laboratory environments, advanced analytical techniques such as gas chromatography (GC), Fourier-transform infrared spectroscopy (FTIR), and mass spectrometry (MS), including combined GC–MS systems, are used to accurately identify gaseous species and characterize degradation pathways. Although these techniques are not suitable for direct integration into battery packs, they play a crucial role in validating sensor performance and establishing detection thresholds for deployable monitoring systems [16].

Each sensing approach involves inherent trade-offs in terms of selectivity, environmental robustness, cost, and power consumption. NDIR CO<sub>2</sub> sensors provide high selectivity and stability but typically require higher power and cost. MOS sensors offer low-cost implementation but are prone to baseline drift and require periodic recalibration. MEMS hydrogen sensors combine fast response with low power consumption and strong relevance for safety monitoring, while MEMS pressure sensors enable reliable detection of mechanical changes within the battery enclosure. However, since certain failure mechanisms may produce gaseous emissions before noticeable changes in temperature or pressure occur, the most effective diagnostic performance is achieved through multi-sensor integration. The combined

use of temperature, pressure, and gas sensing provides comprehensive early-warning capability across multiple degradation pathways.

Gas sensors play a particularly important role in detecting hazardous emissions associated with elevated temperatures and material decomposition in lithium-ion batteries. These emissions may include hydrogen, carbon monoxide, VOCs, and hydrocarbon species released during venting or thermal runaway events [21]. Ongoing developments in commercial sensor technologies, as reflected in recent manufacturer datasheets and product documentation, continue to improve sensitivity, miniaturization, and multi-gas detection capabilities [84 - 89].

A significant emerging trend is the integration of Internet of Things (IoT) technologies into sensing platforms. IoT-enabled sensors support real-time monitoring, wireless communication, and data-driven diagnostics, enabling continuous tracking of battery performance and safety parameters. This is particularly relevant for applications such as electric vehicles, wearable electronics, and industrial energy systems, where compact, low-power, and reliable sensing solutions are required [29]. These developments contribute to the advancement of intelligent battery management systems capable of predictive maintenance and enhanced operational safety.

### **5.3 Practical Implementation of a Multi-Sensor Early Warning System for Lithium-Ion Battery Safety in EV and ESS Applications**

To enable early detection of battery failure and thermal runaway, temperature monitoring should be implemented at the cell level or across small cell groups. This is typically achieved using NTC thermistors or RTDs placed at locations most prone to peak temperature development. For electric vehicle (EV) and energy storage system (ESS) applications, sensors must be automotive-grade and AEC-qualified to ensure reliability under demanding operating conditions. In practice, widely adopted solutions include NTC thermistor assemblies from vendors such as Ametherm or Littelfuse [1].

In addition to temperature sensing, pressure monitoring within the battery enclosure provides critical diagnostic information. MEMS-based battery-pack pressure monitoring sensors (BPMS) can be installed in the enclosure headspace or near venting locations. Sensors specifically designed for battery safety applications, such as the Honeywell BPS or NXP BPMS

families, offer compatibility with battery management systems (BMS) and automotive communication protocols. These devices enable detection of abnormal pressure rise and over-pressure conditions associated with internal cell faults [6].

Gas sensing further enhances early fault detection by identifying decomposition products. A MEMS hydrogen sensor should be positioned within the pack headspace or airflow channels, as hydrogen is often released during the initial stages of failure (e.g., Posifa PGS4100 or equivalent). Additional gases, including CO, CO<sub>2</sub>, and volatile organic compounds, can be detected using NDIR CO<sub>2</sub> sensors (e.g., Sensirion SCD30) and VOC sensor arrays based on MOS or electrochemical technologies. Experimental evidence indicates that CO<sub>2</sub> detection is particularly effective for identifying early venting events in lithium-ion cells [6].

Optimal sensor placement is essential for reliable operation. Gas sensors should be located where vented gases are likely to accumulate, such as along vent channels, at the top of the enclosure, or downstream of vent outlets. A controlled headspace or guided airflow path should be maintained to ensure gas delivery to the sensors. At the same time, sensors must be protected from direct exposure to electrolyte liquids and should not be placed in uncontrolled coolant streams; protective housings or gas-permeable membranes are commonly employed. For high-value systems, redundant sensor configurations are recommended to improve robustness and fault tolerance [7].

Sensor outputs, transmitted via CAN bus or SPI/I<sup>2</sup>C interfaces, are integrated into the BMS and processed using diagnostic algorithms. Key methods include rate-of-change analysis (e.g.,  $dT/dt$ ,  $dP/dt$ ), baseline correction for drift-sensitive sensors (particularly MOS types), and multi-sensor data fusion. For example, detection of trace hydrogen may trigger an elevated monitoring state, while concurrent hydrogen detection and rapid temperature increase may initiate protective actions such as system isolation. Selection of appropriate gas indicators and threshold values should be supported by laboratory validation techniques, including gas chromatography (GC) and Fourier-transform infrared spectroscopy (FTIR) [23].

Maintenance considerations include periodic calibration or auto-zeroing of gas sensors, although NDIR CO<sub>2</sub> and MEMS hydrogen sensors typically require less frequent recalibration. Sensor replacement should be incorporated into routine servicing schedules, and systems should include self-diagnostics as well as humidity and temperature compensation to mitigate long-term drift [6].

In summary, a practical and implementable monitoring framework combines cell-level temperature sensing, enclosure pressure monitoring, and multi-gas detection within a unified BMS architecture. Supported by sensor fusion algorithms and appropriate calibration strategies, this approach enables reliable early warning of battery failure mechanisms in EV and ESS applications [23].

## 6 Gas Sensor Calibration

Gas sensor calibration practice is very important in the modern world. Measurement is based on the output of the sensor with respect to a known concentration of gas. Frequently, enabling the correct measurement range will require sensitivity calibration already set in. For this to obey any sane principle, assures the guaranteed measuring outcome exceeds estimated levels; all possible parallel interferences cannot vary with regards to ages and conditions. Implementation of gas sensors without doubt requires proper calibration and in the fields of environmental evaluation, diagnostics to illness in people, health and safety at work [35].

The introduction is a summary of why a gas sensor must receive calibration in conjunction with sensitivity. In general, with no calibration done, outputs provided by the gas sensor are flawed, thus telling us reliability is going to differ with lack of proper measurement. It goes further to show that calibration causes great improvement in reliability and trustworthiness [35].

### 6.1 Calibration is Required

Calibration is completed by measuring the gas sensor's readings against a standard concentration to ensure it is accurately capturing values. In the absence of calibration, the drift of sensors (which happens due to time) can create significant errors. Factors like humidity, temperature, and environmental pressure can influence the sensor readings and need to be controlled during calibration. Sensors are calibrated in set conditions using certified calibration gases or dynamic calibration systems. Regular calibration is essential for all sensors, particularly those used in critical monitoring applications like toxic gas monitoring. Calibration ensures that the sensor does not capture gas concentrations outside a predefined range and that it counteracts drift by realigning the sensor's output to known levels [11]. Gas sensors are vital for monitoring the status of a battery and its safety all the time. At present, safety batteries are present externally in battery packs to look out for gases being vented as a sign of overheating or deterioration. These implementations depend mainly on established sensors like electrochemical, MOS, and NDIR types, which work dependably but provide notice a little later [31]. Work in the future will involve adding compact gas sensors able to follow changes in gas concentrations during the very start of decomposition. With these sensors, it will soon be possible to monitor a battery's health using constant feedback from the battery's electrochemistry [30]. Gas sensors are sensitive to environmental conditions, which affects their accuracy. Therefore, precise calibration protocols are required to ensure reliability. In EVs,

calibration may be coupled with temperature sensors and BMS analytics for robust performance under dynamic operating conditions [10].

## 6.2 Calibration Strategies

Gas sensor calibration and compensation strategies are crucial to maintaining measurement accuracy and reliability in practical applications. Initial factory calibration is typically performed using standard gas mixtures to establish reference baselines and ensure sensor uniformity across production batches. However, baseline drift compensation becomes necessary over time, as long-term exposure to operational environments or sensor ageing can gradually alter response characteristics. To address environmental variability, humidity and temperature restitution is often implemented through internal correction algorithms that dynamically adjust sensor outputs under changing ambient conditions. Furthermore, field calibration protocols enable recalibration either manually or automatically, utilizing software-based models or stored reference gases to restore accuracy during deployment. In real-world applications, sensor arrays combined with data fusion techniques are increasingly employed to enhance reliability and selectivity. Advanced calibration methods leveraging artificial intelligence (AI) and machine learning (ML) facilitate the interpretation of complex gas patterns and their correlation with specific fault modes. These developments have particular relevance in second-life battery management and embedded diagnostic systems for electric vehicles (EVs), where precise gas monitoring supports safety and performance optimization [36].

## 7 Gas Sensor in Battery System

In battery applications, gas sensors serve several key objectives. First, they enable early detection of battery degradation by identifying chemical byproducts generated during electrolyte decomposition and electrode deterioration [37]. Second, they contribute to enhancing battery safety by detecting gas evolution, thereby preventing hazardous incidents such as thermal runaway or explosions. Third, gas sensors assist in maximizing battery lifespan by identifying degradation-related gases, which allows for the implementation of preventive maintenance strategies to extend cell longevity. Finally, continuous and real-time monitoring of battery conditions is facilitated by advanced gas sensor technologies, providing critical input to the battery management system (BMS) for improved operational reliability [2].

Commercial gas sensors have been developed for detecting gas emissions associated with battery degradation. These sensors are then classified according to the physics of their operation or the identity of the gas molecule toward which they are targeted [32].

Electrochemical gas sensors as illustrated in Figure 7, detect target gases through electrochemical redox reactions at the sensor electrode. An electrical signal proportional to the concentration of the gas is generated from the oxidation or reduction reaction occurring at the electrode. They show very good levels of sensitivity and selectivity toward gases from other sources, such as CO and H<sub>2</sub>, which makes them suitable for applications in battery monitoring [26, 57]. With this, they suffer from cross-sensitivity in some cases, and calibration is important and needs to be carried out regularly.

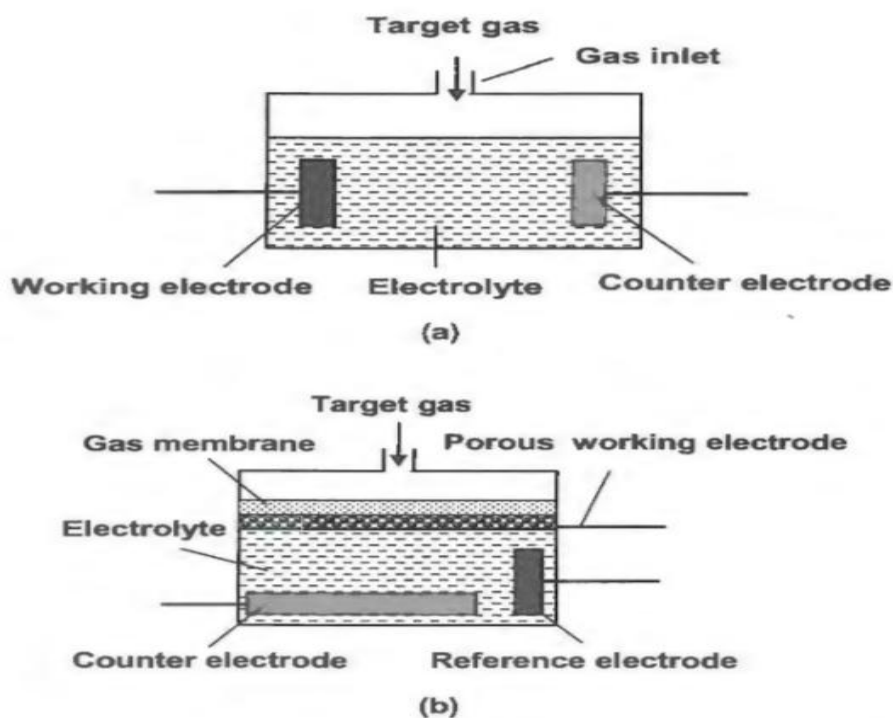


Figure 7. a) Schematic Representation of an Electrochemical Gas Sensor b) Three Electrode Configurations.[57].

## 7.1 Gas Sensor Principle and Application

Gas sensors and batteries are particularly important in consumer electronics, industrial safety, transportation, and healthcare. Batteries generate and/or store energy for both portable and stationary equipment, whilst sensors detect and monitor gases associated with the environment and processes [32].

Gas sensors detect gases by converting chemical interactions into measurable electrical signals. The most common types include electrochemical sensors, metal oxide semiconductor (MOS) sensors, infrared (IR) sensors, catalytic bead sensors, and photoionization detectors (PID) [38].

In MOS sensors, semiconductor particles typically tin dioxide are heated in air, causing oxygen adsorption on their surfaces through electron capture. The resulting depletion layer depends largely on particle size: for nanoscale particles (tens of nanometers), the depletion region can extend across the entire particle volume, yielding high sensitivity. In larger particles, depletion is limited to the particle surface. Detection mechanisms differ across sensor types: electrochemical sensors rely on redox reactions, MOS sensors detect changes in electrical

resistance, IR sensors measure gas absorbance, and PIDs ionize volatile gases with ultraviolet light.

Gas sensors have diverse commercial applications. In industrial safety, they detect hazardous gases such as CO, H<sub>2</sub>, and CH<sub>4</sub>; in environmental monitoring, they measure VOCs, NO<sub>x</sub>, O<sub>3</sub>, and CO<sub>2</sub> emissions; in medical settings, they monitor anesthetic gases and enable breath analysis; in the automotive sector, they track cabin air quality and optimize air-fuel mixtures; and in consumer electronics, they are used in smoke detectors, air purifiers, and smart-home devices. Across these applications, gas sensors play a critical role in enhancing both performance and safety, improving comfort and protection in everyday life [39].

## 7.2 Integration of Temperature Sensing Within Battery System

Monitoring internal temperature is a critical aspect of ensuring the safety, performance, and lifetime of lithium-ion (Li-ion) batteries. Internal temperature data, when transmitted to the battery management system (BMS), enables active regulation of charging and discharging rates, activation of thermal management systems, and early detection of potentially hazardous conditions. Consequently, effective thermal monitoring significantly enhances the safety, efficiency, and durability of the battery pack [7, 79].

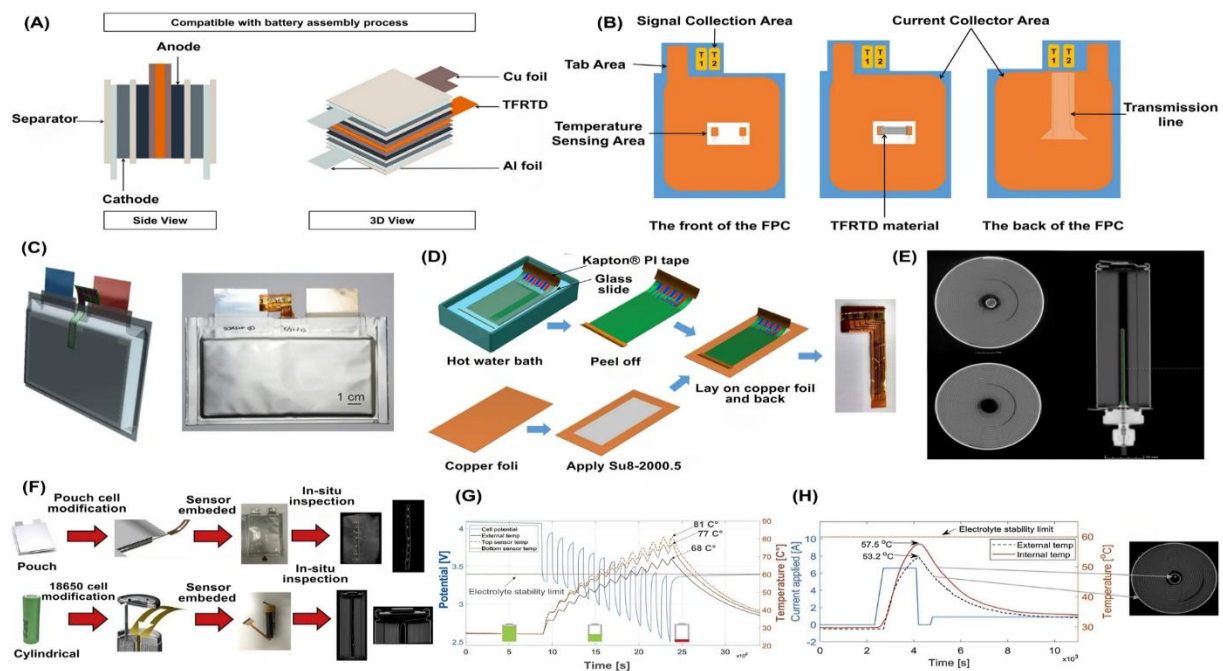


Figure 8. Schematic Presents The Integration of LiB with Temperature Sensors in Different Stages. [25].

Figure 8 illustrates the integration of temperature sensors directly within lithium-ion cells for real-time monitoring. Panels A–H depict the fabrication, embedding, and diagnostic evaluation of flexible temperature sensors in both pouch and cylindrical configurations, highlighting their role in improving safety and performance under dynamic operating conditions.

Traditional surface-mounted sensors often fail to detect localized hot spots that develop within cells. To address this limitation, optical fiber-based sensing technologies including Fiber Bragg Grating (FBG), Fabry–Perot interferometric (FPI), and distributed optical fiber sensing (DOFS) have emerged as promising solutions for in situ temperature measurement. These sensors can be embedded directly into battery cells, offering high spatial resolution, fast response times, and immunity to electromagnetic interference. As such, they enable detailed mapping of internal thermal gradients and provide critical insight into degradation mechanisms, thereby supporting more accurate inputs to the BMS [7].

Despite these advantages, several technical challenges remain. Integration difficulty is a primary concern, as inserting optical fibers into cells may disturb electrode structures, necessitating the use of thin and flexible fibers. Electrolyte compatibility also presents challenges, often requiring protective coatings such as polyimide to prevent chemical degradation. Furthermore, cross-sensitivity between strain and temperature can affect measurement accuracy; this is commonly mitigated through hybrid sensing configurations (e.g., combined FBG and FPI systems). While distributed sensing techniques such as optical frequency-domain reflectometry (OFDR) provide extensive spatial coverage, their cost and scalability currently limit widespread industrial adoption. Nevertheless, recent studies demonstrate significant progress toward durable and cost-effective fiber-based sensors for embedded battery diagnostics [7].

Overall, optical fiber sensing represents a powerful approach for internal state monitoring, enabling detection of thermal gradients, pressure evolution, and structural changes. Continued advancements in sensor integration, material compatibility, and signal processing are expected to facilitate reliable, real-time internal diagnostics in next-generation Li-ion battery systems.

### 7.3 Internal Temperature Monitoring in Li-ion Batteries

Lithium-ion (Li-ion) batteries generate heat during both charging and discharging due to internal electrochemical and resistive losses. Because the internal temperature often exceeds the surface temperature, localized hot spots can develop within the cell. Elevated internal temperatures accelerate aging through mechanisms such as solid–electrolyte interphase (SEI) layer thickening and unwanted side reactions, while also posing serious safety risks, including fire, explosion, and thermal runaway. Temperature gradients can further induce uneven electrode degradation, reducing cycle life and overall performance. Consequently, continuous monitoring of internal temperature is essential to ensure optimal battery operation, longevity, and safety [5].

Most conventional battery packs rely on surface-mounted sensors, such as thermocouples or resistance temperature detectors (RTDs). However, these sensors measure only the external temperature and cannot directly detect internal hot spots. Because heat must diffuse from the cell's core to the surface, surface sensors inherently lag behind real internal temperature changes, potentially failing to provide early warnings of dangerous overheating.

To address these limitations, fiber-optic sensors have emerged as a promising solution for internal temperature monitoring. Fiber-optic sensors are lightweight, chemically stable, thin, and flexible, allowing them to be embedded within the cell without compromising electrochemical performance. They rely on light reflection or interference rather than electrical signals, making them immune to electromagnetic interference. Moreover, fiber sensors offer distributed sensing along their length, high spatial resolution, rapid response, and the ability to perform multi-point measurements.

Several fiber-optic technologies are relevant for battery applications. Fiber Bragg Grating (FBG) sensors measure temperature by detecting shifts in the wavelength of reflected light, though compensation for strain effects is required. Fabry–Perot Interferometers (FPI) detect temperature or pressure through interference patterns in an optical cavity, enabling local monitoring within the battery. Advanced distributed fiber sensing methods, such as optical frequency domain reflectometry (OFDR) and Rayleigh or Brillouin scattering, allow continuous spatial mapping of temperature along the fiber, providing detailed insights into internal hot-spot formation.

Monitoring internal temperature is critical for understanding and mitigating degradation. As batteries age, increased internal resistance generates additional heat, and abnormal thermal regions can indicate localized electrode deterioration. When combined with other diagnostic techniques such as pressure or strain monitoring and differential voltage analysis fiber-optic data enables more accurate state-of-health (SOH) assessment and early detection of potential failures [40].

For reliable integration, sensors must remain chemically inert with respect to the electrolyte and maintain a compact, non-intrusive form factor that does not compromise cell performance. Ideally, such devices are miniaturized, potentially to the scale of microelectromechanical systems (MEMS), ensuring compatibility with modern battery architectures [41].

#### **7.4 Comparison of External (Pack-Level) and Internal (Cell-Level) Sensing in Lithium-Ion Batteries**

To contextualize the role of gas sensing within battery monitoring architectures, it is useful to distinguish between sensing strategies implemented external to the cell or pack and those embedded internally at the cell level. External sensing approaches typically monitor macroscopic indicators such as pack temperature, pressure, or vented gas composition, offering relative ease of integration and lower system complexity. In contrast, internal sensing enables direct access to early electrochemical and chemical signatures of degradation, potentially providing faster response times and higher sensitivity to incipient failure modes. However, these benefits are often accompanied by increased design complexity, integration challenges, and cost considerations. The table 3, below compares external and internal sensing capabilities across key performance and implementation metrics, including response time and sensitivity, system complexity, safety detection effectiveness, and cost, highlighting the trade-offs relevant to sensor selection in advanced battery systems [33].

Table 3. External and Internal Gas Sensors in Batteries

<b>Feature</b>	<b>External Gas Sensors</b>	<b>Internal Gas Sensors</b>
Response time	Typically delayed, as detection depends on gas diffusion from the cell to the external environment.	Provides near real-time detection through direct exposure to internal gases.
Sensitivity	Generally low to moderate, limited by gas concentration gradients and diffusion barriers.	High sensitivity due to proximity to the gas generation source.
System complexity	Relatively simple, with minimal integration requirements.	More complex, as sensors must be integrated within the battery cell or module.
Safety detection capability	Primarily detects major events such as venting or thermal runaway.	Enables early detection of degradation precursors and electrolyte decomposition.
Cost	Cost-effective and commercially mature.	Currently high, as technologies remain in the development and validation stages.

Table 3. presents a comparative overview of external and internal gas sensors used for lithium-ion battery monitoring. External sensors generally exhibit delayed response times because gas detection relies on diffusion through the battery casing, while internal sensors provide real-time monitoring by directly sampling gases generated within the cell. Although external configurations are simpler and more cost-effective, they typically offer lower sensitivity and are limited to detecting severe events such as venting or thermal runaway. In contrast, internal sensors demonstrate higher sensitivity and faster response, allowing the detection of early degradation indicators and electrolyte decomposition. However, these advantages come with increased design complexity and integration challenges, as well as higher developmental costs [33, 59].

## 7.5 Classification of Gas Sensor Technologies based on Operating Principles and Target Gases

Table 4 presents a classification of commonly employed gas sensor technologies based on their operating principles and target gas species. The table compares electrochemical, metal oxide semiconductor, and non-dispersive infrared sensors, highlighting the fundamental sensing mechanisms that govern their response to specific gaseous analytes. Such a classification provides a concise framework for understanding the functional differences among gas sensing approaches and their suitability for detecting key gas signatures relevant to safety-critical applications, including battery health and safety monitoring.

Table 4. Classification of Gas Sensors

Sensor Type	Target Gases	Principle of Operation
Electrochemical sensors	H <sub>2</sub> , CO, NO <sub>x</sub>	Target gases undergo electrochemical reactions at the electrodes, producing a measurable current proportional to gas concentration.
Metal Oxide Semiconductor (MOS) sensors	VOCs, hydrocarbons	Gas molecules adsorb onto the semiconductor surface, altering its electrical resistance as a function of gas concentration.
Non-Dispersive Infrared (NDIR) sensors	CO <sub>2</sub> , CH <sub>4</sub>	Target gases absorb infrared radiation at characteristic wavelengths; the reduction in transmitted IR intensity is used to quantify concentration.

Gas sensing technologies can be broadly categorized based on their underlying detection mechanisms. Electrochemical sensors operate by inducing redox reactions of target gases such as hydrogen (H<sub>2</sub>), carbon monoxide (CO), and nitrogen oxides (NO<sub>x</sub>) at electrode surfaces, generating a current that is directly related to gas concentration. Metal Oxide Semiconductor (MOS) sensors detect volatile organic compounds (VOCs) and hydrocarbons through changes in surface resistance resulting from gas adsorption on the sensing layer. In contrast, Non-Dispersive Infrared (NDIR) sensors identify gases such as carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) by measuring the absorption of infrared light at characteristic wavelengths specific to each gas species.

External sensors are important component of Battery Management Systems (BMS) to check the whole battery's condition. Though these sensors are simple to use and affordable, they do not accurately detect problems early on since it takes some time for gases to be detected outside the car. When it comes to safety in EVs and grid storage, they are fine; however, they have restricted ability to diagnose errors [4].

## **7.6 Measurement of Gas Emission in Lithium-Ion Batteries Using Metal Oxide Semiconductors Sensors**

Metal Oxide Semiconductor (MOS) sensors are widely used in portable gas detection systems due to their low cost, simplicity, and reliable performance. In lithium-ion (Li-ion) batteries, these sensors monitor gases such as hydrogen ( $H_2$ ), carbon dioxide ( $CO_2$ ), carbon monoxide (CO), and volatile organic compounds (VOCs) emitted during degradation processes or thermal events. By detecting these emissions, MOS sensors provide critical information on battery health and enable early prediction of failure [42].

The primary variables measured with MOS sensors in battery monitoring include gas concentration, rate of gas evolution, time of first gas detection, and battery capacity loss. Gas concentration is typically expressed in parts per million (ppm) or moles per ampere-hour (mol/Ah), while the rate of gas evolution quantifies how quickly gases are generated during charging, discharging, or over the battery lifecycle. The time of first detection indicates how early the sensor responds to gas release compared to conventional voltage, current, or temperature measurements, offering a predictive insight into early-stage degradation. Battery capacity loss, often expressed as a percentage, can be correlated with the cumulative gas evolution to assess the extent of deterioration [42].

MOS sensors' performance is evaluated through metrics such as sensitivity, response time, recovery time, limit of detection (LOD), selectivity, and stability over repeated cycles. Sensitivity ( $S$ ) is defined as the ratio of resistance in air ( $R_a$ ) to resistance in the target gas ( $R_g$ ) for reducing gases, or  $R_g/R_a$  for oxidizing gases, indicating the magnitude of the sensor's response. Response time ( $t_{res}$ ) measures the duration required to reach 90% of the maximum resistance change upon exposure to the target gas, while recovery time ( $t_{rec}$ ) quantifies the time needed to return to baseline after gas removal. LOD refers to the minimum gas concentration that can be reliably detected, and selectivity represents the sensor's ability to

distinguish the target gas from interfering species. Stability, or drift, describes changes in sensitivity over time or across multiple measurement cycles [27].

During thermal runaway in Li-ion cells, gas emissions can reach 0.1 to 7 mol per Ah of capacity according to Schulte-Albert et al., (2021). MOS sensors are capable of detecting ppm-level H<sub>2</sub> and VOCs before venting occurs, whereas conventional temperature sensors may respond only seconds or minutes later. Depending on the sensor material and target gas, resistance changes can reach up to tenfold at ppm concentrations [24].

Beyond battery monitoring, MOS sensors have applications in industrial safety, air quality monitoring, and medical diagnostics. In all these contexts, key measured variables include gas concentration, reaction rate, resistance change relative to baseline, response and recovery times, and cumulative gas generation. In lithium-ion batteries specifically, these measurements allow for real-time assessment of degradation processes, predictive maintenance, and improved operational safety [27].

## 8 Current Progress in Gas Sensors-Based Degradation Monitoring of Lithium-Ion Batteries

Several recent experimental and review studies have been reported to evaluate the feasibility of gas sensing for early fault detection and degradation monitoring in lithium-ion batteries. These works are particularly relevant because they provide both fundamental insights into gas-generation mechanisms and practical assessments of sensor performance under realistic operating and failure conditions. The following selected studies are presented to highlight key advancements, limitations, and design considerations in gas sensor-based battery diagnostics.

One of the most frequently cited experimental studies on early detection of failing automotive lithium-ion batteries evaluated a range of commercial gas sensors in relation to key failure mechanisms, including electrolysis, electrolyte vapor generation, venting, and thermal runaway [39]. The results demonstrated that gas sensors are capable of identifying certain failure modes at an early stage; however, the accuracy and timeliness of detection depend strongly on both the specific failure pattern and the sensor type employed. It was further emphasized that conventional battery management system (BMS) parameters such as voltage, current, and temperature are often insufficient to detect some failure scenarios prior to the onset of thermal runaway. In contrast, gas sensors provide an additional detection channel capable of identifying pre-failure chemical activity, although not all failure pathways are immediately detectable through gas signatures alone [39].

A more recent mini-review summarized advancements in early-stage detection of thermal runaway gases in Li-ion batteries, with particular focus on semiconductor gas sensors, especially metal-oxide-based systems [40]. These sensors have been applied to detect characteristic gases such as hydrogen ( $H_2$ ), carbon monoxide (CO), carbon dioxide ( $CO_2$ ), and volatile electrolyte vapors generated during the initial stages of failure. Gas generation mechanisms and suitable sensor configurations were discussed, along with practical limitations including cross-sensitivity, calibration drift, and the low concentration of diagnostic gases during early degradation, all of which constrain detection reliability in real-world applications [40].

A comprehensive review of gas detection technologies for identifying the onset of thermal runaway examined both sensor types and early-warning system designs [41]. The analysis focused on the evolution of gas emissions during failure and evaluated various detection

modalities, including electrochemical, non-dispersive infrared (NDIR), optical, and semiconductor sensors. It was highlighted that gas evolution can serve as a viable early-warning signal, as volatile decomposition products typically emerge before any significant temperature increase. However, challenges such as insufficient sensitivity, slow response times, and integration difficulties in commercial systems remain significant barriers [41].

In a broader context, advanced sensing technologies for monitoring the state of lithium-ion batteries have been reviewed, covering multiple sensor modalities including mechanical stress/strain, temperature, and gas evolution [42]. These studies highlight how gas sensors can complement conventional diagnostic methods to improve the accuracy of state-of-health (SOH) and state-of-safety (SOS) assessments.

Fault detection in large battery packs has also been investigated using combined force and gas sensing approaches [43]. It was demonstrated that internal short circuits generate gaseous products such as CO<sub>2</sub> and induce measurable mechanical swelling. Since voltage deviations in a single defective cell may be masked by surrounding healthy cells, enclosure-level gas sensors were proposed as an effective solution for improved fault localization through detection of accumulated gas emissions [43].

Gas analysis has also been explored as a diagnostic tool for understanding degradation mechanisms rather than solely for failure detection [44]. By examining gas composition profiles during cycling, it is possible to establish relationships between gas evolution and electrochemical aging processes, providing deeper insight into material degradation pathways within the cell.

Finally, gas evolution behavior under various operational and abuse conditions has been systematically investigated, identifying key gaseous species such as CO<sub>2</sub>, CO, H<sub>2</sub>, and light organic compounds generated during charging, discharging, and overcharge events [5]. These findings confirm that gas generation is closely linked to battery aging, electrolyte instability, and failure progression, reinforcing the importance of gas analysis as both a diagnostic and prognostic indicator.

## 8.1 Advantages of Using Gas Sensors in Battery Monitoring

Early warning of internal failure or material decomposition is critical for preventing catastrophic events such as thermal runaway. Gas sensors provide a unique advantage in this regard, as they can detect volatile decomposition products and other chemical byproducts of degradation prior to noticeable changes in temperature or voltage. This capability offers a significantly longer reaction window compared to conventional monitoring approaches [41].

Complementary to existing Battery Management System (BMS) metrics namely voltage, current, and temperature gas sensing introduces a chemical diagnostic dimension that enhances the overall accuracy of failure detection. Traditional electrical and thermal sensors may overlook certain internal failure modes, whereas gas sensors enable the identification of subtle chemical signatures associated with early-stage degradation. Importantly, many gas detection systems (e.g., Li-ion Tamer) can be externally mounted, eliminating the need for direct electrical connection to individual cells [43]. This non-invasive configuration simplifies system integration, retrofitting, and redundancy design.

Recent advances in sensing materials and technologies have further improved the sensitivity and selectivity of gas detection for battery applications. Nanostructured metal-oxide semiconductors (MOS), such as SnO<sub>2</sub> nanoboxes, ZnO, and WO<sub>3</sub>, exhibit enhanced response characteristics and lower detection limits. In addition, fiber-optic monitoring systems allow real-time, in situ detection within operating cells. Emerging self-powered sensors capable of harvesting energy from ambient vibrations or heat further reduce power consumption and increase deployment flexibility. Hybrid sensor arrays combined with artificial intelligence (AI) techniques enhance gas selectivity and enable predictive diagnostic capabilities.

Sensors designed for harsh environments featuring flexibility, corrosion resistance, and high-temperature tolerance address key challenges in battery monitoring. Gas detection serves multiple functions, leak detection of electrolyte vapors (e.g., ethyl methyl carbonate), early thermal runaway warning through detection of gases such as H<sub>2</sub>, CO, and CO<sub>2</sub>, health diagnostics via monitoring of gas evolution during charge–discharge cycles, and safety management through automated shutdown or cooling when gas concentrations exceed critical thresholds.

Strategic placement of multiple sensing points or zonal deployment within battery packs enables precise localization of modules or racks emitting abnormal gases, facilitating targeted interventions. Early detection of flammable gases (e.g., H<sub>2</sub> and volatile organic compounds) is particularly crucial in large-scale Li-ion battery systems, such as containerized storage units. Such detection can automatically trigger mitigation responses such as ventilation or system shutdown before ignition risks escalate. Furthermore, identifying the specific types of gases evolved (e.g., CO, CO<sub>2</sub>, hydrocarbons) provides diagnostic insight into underlying failure mechanisms, distinguishing between electrolyte decomposition, solid electrolyte interphase (SEI) breakdown, or other internal reactions, and aiding in the assessment of failure severity [34].

## 8.2 Gas Monitoring in Battery Recycling

During the recycling of lithium-ion batteries, particularly during disassembly, crushing, and material recovery stages, the mechanical damage inflicted on cells can lead to the rupture of casings and exposure of internal components. This process often triggers the decomposition of electrolyte and electrode materials, resulting in the release of hazardous gases, a phenomenon that poses significant safety and environmental concerns. The main gases evolved include flammable gases such as hydrogen (H<sub>2</sub>), which present an explosion risk; toxic gases such as carbon monoxide (CO), which are harmful even at low concentrations; and corrosive, highly toxic gases such as hydrogen fluoride (HF), produced from the degradation of lithium hexafluorophosphate (LiPF<sub>6</sub>) salt in the electrolyte. Inhalation of HF, even in trace amounts, can cause severe respiratory and tissue damage, emphasizing the critical need for gas monitoring during recycling operations [73 - 75].

Gas detection and monitoring systems play a vital role in optimizing recycling processes and ensuring workplace safety. First, they serve as early warning systems, protecting workers from exposure to poisonous or explosive gases. Second, real-time gas monitoring assists in process control, allowing operators to adjust temperature, pressure, or mechanical intensity if abnormal gas emissions indicate overheating or excessive reaction rates. Third, detecting corrosive gases such as HF at an early stage helps prevent equipment degradation, extending the operational life of recycling machinery. Finally, maintaining stable environmental conditions and

minimizing gas emissions contribute to higher-quality material recovery, enabling the efficient reclamation of valuable elements such as cobalt and nickel from spent cells.

Therefore, implementing robust gas sensing technologies such as metal oxide semiconductor (MOS) sensors, electrochemical sensors, and infrared spectroscopic systems within recycling facilities enhances both safety and process optimization. Continuous gas monitoring not only safeguards human health but also supports the development of sustainable, closed-loop battery recycling systems that align with circular economy principles [73 - 75].

### **8.3 Technical Limitations, Practical Challenges, and Mitigation Strategies in Gas Sensing Technologies**

Table 5 summarizes the key limitations and practical challenges associated with gas sensing technologies, along with representative mitigation strategies and ongoing research directions. The challenges highlighted include the detection of gases at extremely low concentrations during early emission stages, cross-sensitivity and selectivity limitations arising from interfering species, and long-term sensor drift and calibration instability. By pairing each challenge with corresponding mitigation approaches, such as advanced sensing materials, signal processing techniques, and data-driven calibration methods, the table provides a concise overview of current research efforts aimed at improving the reliability and applicability of gas sensor-based monitoring systems.

Table 5. Limitations and Challenges Regarding Gas Sensors [46 - 50].

Challenge	Explanation / Examples	Mitigation or Research Direction
Low concentration at early detection stages	At the initial stages of material decomposition or gas emission, the concentration of target gases can be extremely low (in the parts-per-million [ppm] or sub-ppm range). Such low levels often fall below the detection limits of conventional gas sensors, reducing their effectiveness in early warning systems.	Research has focused on developing ultra-sensitive sensing materials (e.g., nanostructured metal oxides, 2D materials), preconcentration techniques, and signal amplification or filtering methods to enhance detection at trace levels.
Cross-sensitivity and selectivity issues	Many gas sensors, particularly metal oxide (MOx) sensors, exhibit non-specific responses to various interfering gases such as volatile organic compounds (VOCs), carbon monoxide (CO), and humidity. This overlap in sensitivity can lead to misinterpretation of gas identity and concentration.	To mitigate cross-sensitivity, researchers employ sensor arrays (electronic noses) combined with machine learning algorithms, pattern recognition, and baseline drift compensation. These methods help differentiate between gases and improve selectivity.
Sensor drift, ageing, and calibration instability	Over time, sensors can experience performance degradation due to environmental exposure (temperature, humidity, dust) and chemical changes in sensing materials. This drift leads to inaccurate readings and necessitates frequent recalibration.	Strategies to address drift include adaptive calibration algorithms, self-calibrating sensor arrays, and data-driven correction techniques. Regular maintenance schedules and material engineering (e.g., doping or surface modification) can also enhance long-term stability.

## 8.4 Commercial Industrial Systems

Gas sensors play an increasingly critical role in the safety and diagnostic functions of battery management systems (BMS), particularly in lithium-ion (Li-ion) energy storage technologies. Their integration enhances both operational safety and predictive maintenance by enabling real-time detection of gaseous emissions associated with cell degradation and failure. Different sensor technologies offer complementary capabilities for detecting specific gas species. For example, non-dispersive infrared (NDIR) sensors are commonly used for detecting carbon dioxide (CO<sub>2</sub>) buildup, electrochemical sensors are applied for sensing oxygen (O<sub>2</sub>) and carbon monoxide (CO), and metal oxide semiconductor (MOS) sensors are suitable for detecting volatile organic compounds (VOCs). The continuous monitoring of gas composition provides valuable insights into the state of health (SOH) of batteries, helping to prevent catastrophic failures and ensure safe operation.

During degradation and failure processes, Li-ion batteries emit various gases such as oxygen, carbon dioxide, hydrogen, carbon monoxide, and volatile organic compounds [36]. Monitoring these emissions allows early identification of abnormal conditions, often well before a thermal runaway event occurs. One of the most well-known commercial systems developed for this purpose is the Li-ion Tamer, originally by Nexceris and currently owned by Honeywell. This “off-gas monitoring” system is designed to detect early indicators of battery failure by measuring gases released from electrolyte vapors and decomposition products prior to a full thermal runaway. According to the company’s product documentation, the system supports a variety of Li-ion chemistries and can be scaled from module level to pack and room-level applications [43]. The manufacturer claims that early detection allows sufficient time for mitigation measures to be implemented, significantly reducing safety risks.

In 2025, Honeywell acquired Li-ion Tamer with the goal of integrating its technology into the company’s broader safety systems portfolio. According to the Honeywell white paper titled “Lithium Ion Battery Off-Gas Monitoring for Battery Health and Safety”, the Off-Gas Monitor platform detects small leaks or gas emissions such as those from electrolyte dissolution before the onset of thermal runaway [44]. Laboratory studies have demonstrated that sensor responses consistently precede the initiation of thermal runaway, confirming the system’s ability to serve as an early-warning diagnostic tool. The platform is designed to interface directly with BMS control logic, integrating alarm systems, automatic shutdown, and false-positive filtering to ensure reliable safety responses.

Although gas sensing for battery health is a relatively new development, similar technologies have long been employed in battery charging rooms particularly for lead-acid systems to detect the buildup of hydrogen ( $H_2$ ) gas. In these installations, electrochemical hydrogen sensors are used to activate ventilation systems or alarms, primarily for fire and explosion prevention rather than for internal state diagnosis. Such applications underscore the long-standing importance of gas detection as a safety measure in battery environments.

In large-scale battery energy storage systems (BESS), gas sensors are often incorporated within the enclosure or safety layers to detect abnormal off-gassing or environmental deviations [45]. These systems must contend with challenges such as temperature, humidity, and pressure fluctuations, which can influence sensor accuracy and stability. Nevertheless, gas monitoring remains a key supplementary safety indicator and an important diagnostic layer within the BESS safety hierarchy.

Recent research has also focused on the development of integrable sensor arrays, capable of monitoring multiple environmental parameters simultaneously such as gas concentration, temperature, and humidity. As illustrated in Figure 9, the DGM10 Double Gas Module, developed by EC Sense, exemplifies this trend toward compact, multifunctional sensing platforms. These easy gas sensors are being explored for integration into battery modules or packaging materials to enable in situ early detection of off-gas emissions [36]. Such multifunctional arrays represent a promising step toward embedded, real-time diagnostic tools capable of enhancing both the safety and health monitoring capabilities of next-generation battery systems.

Recent research efforts are increasingly directed toward the development of multi-parameter integrated sensing systems, capable of simultaneously measuring temperature, pressure, and gaseous species such as volatile organic compounds (VOCs),  $CO_2$ , or  $H_2$  within a single module. In parallel, distributed sensing technologies, such as fiber Bragg grating (FBG) sensors, are being explored to enhance spatial resolution and provide early fault detection across large battery systems, thereby minimizing false positives. [20 - 21].

Among various gas detection strategies, trace hydrogen ( $H_2$ ) monitoring has gained significant attention as an early indicator of internal degradation or failure, owing to its sensitivity and strong correlation with early-stage electrochemical reactions. Several commercially available

MEMS-based hydrogen sensors have already been adapted for integration into battery management systems (BMS), demonstrating their potential for real-time safety diagnostics.

Furthermore, current research emphasizes algorithmic data fusion, in which BMS algorithms integrate multiple sensing parameters such as temperature trends, pressure rate-of-change, and characteristic gas emission patterns to move beyond simple threshold-based alarms. This approach aims to transition from conventional “alarm-only” systems toward actionable early warning frameworks that enable predictive diagnostics and reduce the incidence of false alarms. [20 - 21].



Figure 9. EC Sense Easy Gas Sensors Module [90].

The DGM10 Double Gas Module detects sensor modules, dual gas modules, temperature, humidity, and two gases at the same time. It is an innovative circuit board that optimally integrates a digital Modbus signal output with a cutting-edge sensing device. The module is built on solid polymer electrochemical sensor technology that is highly reliable. The dual gas sensor module converts small sensor signals into standardized digital outputs. As a result, the DGM10 Sensor Module is an intuitive choice for such application.

## 8.5 Cost Analysis

Gas sensors play a critical role in monitoring lithium-ion batteries, particularly for safety, degradation detection, and process optimization. The metal oxide semiconductor (MOS) sensors are the most cost-effective option, typically ranging from \$1 to \$10 per unit, although their high operating temperatures can increase overall system costs. Optical and fiber-optic sensors offer high precision and stability, making them suitable for research and critical safety applications, but they are substantially more expensive, with prices ranging from \$100 to \$1000 per unit. Conducting polymer and carbon nanotube (CNT)-based sensors represent a mid-cost alternative with lower power requirements, though they often exhibit reduced long-term stability. Recent advances combine sensor arrays with artificial intelligence (AI) to enhance selectivity, reduce false alarms, and improve operational efficiency; while these systems involve a higher initial investment, they are cost-effective over time due to reduced maintenance and downtime.

Key performance metrics for gas sensors in battery monitoring include sensitivity, selectivity, response time, stability, operating temperature, and power consumption. Emerging technologies, including self-powered and nanomaterial-based sensors, are expanding the options available for specialized applications. The gas sensor market for battery applications is projected to surpass \$157 million by 2036, reflecting increasing adoption across electric vehicle and energy storage sectors. Understanding the cost-performance trade-offs of different sensor technologies is essential for designing effective and economically viable battery monitoring systems [46].

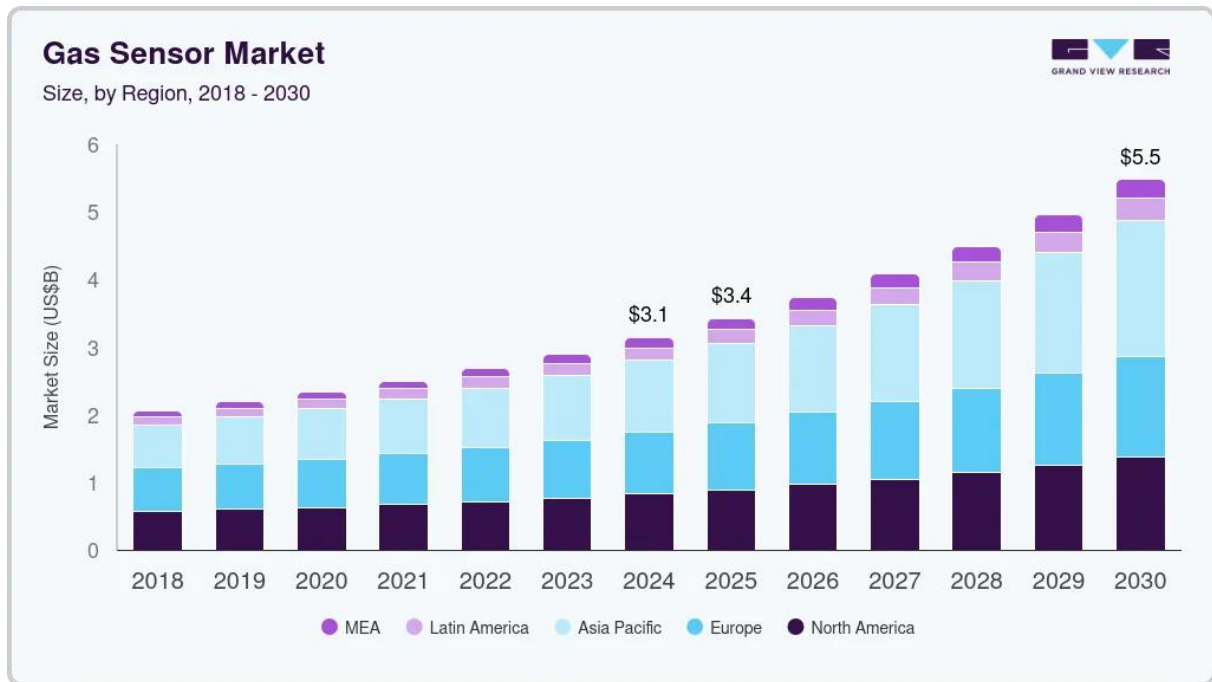


Figure 10. Gas Sensor Marketing Strategies [46].

The chart of Figure 10. reflects how technological advancements and regulatory pressures, specifically in industrialized regions, are most likely to stimulate market expansion. This regional analysis underlines the importance of tailoring gas sensor technologies and marketing strategies according to regions specifically for industrial needs and regulatory environments.

## 9 Discussion and Conversation

### 9.1 How Commercial Gas Sensor Data Can Be Integrated into Battery Management Systems to Improve Safety and Longevity

Lithium-ion batteries (LiBs) have become the cornerstone of modern energy storage technologies, forming the basis of electric vehicles (EVs), renewable energy storage systems, and portable electronic devices. Despite their success, concerns regarding safety and long-term stability persist, particularly because of the risks associated with thermal runaway, electrolyte decomposition, and accelerated degradation under abusive or high-stress operating conditions. The Battery Management System (BMS) serves as the central safety component, monitoring electrical and thermal parameters such as voltage, current, and temperature to ensure stable operation and prevent hazardous events [39].

However, traditional BMS monitoring parameters may not be sufficient to detect the earliest warning signs of failure. The incorporation of commercial gas sensors into BMS architectures introduces a novel dimension to battery diagnostics by detecting chemical precursors of degradation. This approach offers earlier and more sensitive detection of cell abnormalities, enhancing both operational safety and battery longevity.

#### 9.1.1 General Role of Gas Sensors in Battery Safety

Under normal operation, lithium-ion batteries do not produce gaseous emissions. When subjected to stress, such as overcharging, overheating, or internal short-circuiting, however, small quantities of gases including carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), hydrogen (H<sub>2</sub>), and volatile organic compounds (VOCs) are released. These gases are by-products of electrolyte decomposition and electrode degradation, and they serve as early indicators of internal instability.

Commercial gas sensors, originally developed for industrial safety and environmental applications, can be adapted to monitor these emissions within battery packs [29]. Their inclusion enables the BMS to detect faults at the chemical level before they manifest as measurable thermal or electrical anomalies. This early warning capability allows the system to take pre-emptive action such as reducing charge rates, activating cooling mechanisms, or isolating malfunctioning cells hereby preventing escalation to thermal runaway or catastrophic

failure. The addition of gas sensors therefore transforms the BMS from a reactive to a predictive safety management system, providing a critical layer of chemical diagnostics that complements traditional monitoring methods.

### 9.1.2 Integration of Gas Sensors into Battery Management Systems (Data-Driven Perspective)

In current BMS frameworks, sensors monitoring voltage, current, and temperature provide the data required to estimate the state of charge (SOC) and state of health (SOH). The integration of gas sensor data into this framework extends these capabilities by incorporating information about the chemical state of the battery, thereby enhancing diagnostic accuracy [24]. By continuously monitoring trace gases generated from electrolyte decomposition or electrode degradation, the BMS can detect the onset of failure well before conventional electrical or thermal indicators respond.

This integration primarily contributes at the decision-making and control level of the BMS. The detection of trace gases enables early fault identification, allowing the system to predict and mitigate conditions that could lead to thermal runaway. When gas concentrations exceed predefined safety thresholds, the BMS can automatically adjust charging currents or voltages, thereby reducing electrochemical, mechanical, and thermal stress on the cells.

In addition, continuous analysis of gas emission trends supports predictive maintenance strategies by enabling the estimation of degradation rates and facilitating timely maintenance actions, such as cell replacement or system reconfiguration. In emergency scenarios, the BMS can isolate affected cells or activate thermal management systems to prevent fault propagation.

Through this multi-parameter and chemically informed monitoring approach, gas-sensor-integrated BMS architectures establish a more comprehensive safety framework, significantly improving system reliability and extending the operational lifespan of battery packs [24].

### 9.1.3 Practical Applications of Gas Sensors in BMS

The integration of gas sensors into battery management systems (BMSs) has several practical applications across different industries. In electric vehicles, gas sensors capable of detecting CO and H<sub>2</sub> allow the BMS to identify and isolate faulty cells before they compromise the entire pack, thereby reducing the risk of fire and enhancing passenger safety. In large-scale grid

energy storage systems, gas sensing mitigates cascade failures by identifying and controlling the spread of local degradation events, which improves long-term reliability and facilitates the incorporation of intermittent renewable energy sources into the grid. In consumer electronics, the miniaturization of MEMS-based gas sensors allows their incorporation into compact devices such as smartphones and laptops, where they provide an additional chemical safety layer alongside traditional temperature monitoring, with negligible impact on weight or size. These examples highlight the adaptability of gas-sensor-enhanced BMS technology in both stationary and mobile energy storage systems [18, 20].

#### 9.1.4 Integration of Gas Sensors for Monitoring and Extending Lithium-Ion Battery Lifetime

##### 9.1.4.1 Role of Gas Sensors in Battery Monitoring

As lithium-ion batteries age, electrochemical side reactions, overcharging, and thermal stress lead to the generation of gaseous by-products such as CO<sub>2</sub>, H<sub>2</sub>, CH<sub>4</sub>, and VOCs. These compounds serve as sensitive indicators of internal degradation processes that precede measurable changes in voltage or temperature. Gas sensors embedded within or near the battery pack can detect these gases in trace concentrations, providing the BMS with early diagnostic information. Unlike conventional monitoring techniques, gas detection offers insight into the underlying chemical reactions responsible for cell deterioration. By responding promptly to gas emissions, the BMS can dynamically adjust operational conditions, reduce charge rates, activate thermal control mechanisms, or isolate compromised cells, thereby preventing more severe failures such as thermal runaway [47]. Through such real-time chemical monitoring, gas sensors play an indispensable role in enhancing battery reliability and safety [47].

##### 9.1.4.2 Enhancing Battery Longevity and Sustainability

Beyond safety, the integration of gas sensors contributes significantly to extending battery longevity. By preventing premature cell failure, gas-sensor-enabled BMS architectures can extend the operational life of lithium-ion battery packs from approximately eight years to ten or even twelve years. This extension reduces replacement frequency and, consequently, lowers the demand for raw materials such as lithium, cobalt, and nickel. In turn, this alleviates the environmental burden associated with mining and refining these critical materials. The extended operational lifespan also decreases the carbon footprint per kilowatt-hour of energy

delivered and reduces electronic waste. Furthermore, improved monitoring supports the second-life utilization of retired EV batteries for stationary energy storage applications, reinforcing circular economy principles and promoting resource efficiency [48].

#### 9.1.4.3 Challenges and Design Considerations

Despite their advantages, several design challenges must be overcome to achieve large-scale deployment of gas sensors within lithium-ion systems. The longevity of the sensors must match the typical operational lifetime of the battery, which can extend up to fifteen years, while maintaining accuracy without significant signal drift. Optimal placement of sensors is crucial to ensure effective gas detection; positioning them near vent paths or within enclosed areas of the cell can improve response times and sensitivity. Selectivity represents another major challenge since sensors must reliably differentiate between target gases such as H<sub>2</sub> and CO<sub>2</sub> and other volatile organic compounds that may coexist within the system. Advanced materials and self-healing sensor designs, such as field-effect transistor (FET)-based architectures, can mitigate these challenges by enhancing selectivity, stability, and durability over extended operational periods [47].

#### 9.1.5 Example Mechanism and System Response

During the initial stages of electrochemical or thermal stress, slight overheating or overvoltage conditions can trigger electrolyte decomposition, generating gases such as CO<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, and CH<sub>4</sub>. Once released, these gases are detected almost instantaneously by the integrated gas sensors. The BMS interprets these signals and responds by lowering the charging current, activating cooling subsystems, or isolating the defective cell from the pack. This prompt response prevents further degradation and halts the progression toward thermal runaway. Over time, this capability translates into longer battery life, higher charge–discharge cycle counts and improved overall energy efficiency and economic performance [77 - 78].

#### 9.1.6 Environmental and Economic Implications

The integration of gas sensors into battery management systems has far-reaching environmental and economic implications. Real-time gas monitoring facilitates predictive maintenance, thereby reducing unplanned downtime and operational costs while improving the reliability of large-scale energy storage systems. From an environmental standpoint, the ability to prevent

catastrophic failures and extend battery life significantly reduces the number of discarded cells, lowers raw material consumption, and minimizes the carbon footprint associated with battery manufacturing and recycling. Studies indicate that gas-sensor-enabled lithium-ion systems can reduce their environmental impact by up to 20% per kilowatt-hour of energy delivered, aligning with sustainability and circular economy objectives [77 - 78]. In addition, by enabling safer and more controlled operation, gas sensors make it possible to repurpose used EV batteries for stationary applications, thus reducing waste and supporting more sustainable life-cycle management. Ultimately, this approach represents a substantial step toward environmentally responsible and economically viable energy storage technologies [49].

## **9.2 Environmental Influences on Gas Sensor Performance for Battery Degradation Monitoring**

Recently, researchers have increasingly focused on examining how environmental conditions influence the performance of commercial gas sensors used to detect degradation gases emitted from batteries. Gas sensors play a crucial role in monitoring the health of deteriorating batteries by detecting gaseous by-products released during aging and degradation processes. As batteries such as lithium-ion and lead-acid systems age, they produce gases including hydrogen ( $H_2$ ), ammonia ( $NH_3$ ), and volatile organic compounds (VOCs), which result from electrolyte decomposition, corrosion, and internal chemical reactions. Detecting these gases in their early stages is essential for identifying the onset of degradation and preventing safety hazards such as leakage, venting, or explosion. However, the accuracy and reliability of gas sensors can be significantly affected by environmental parameters such as temperature, humidity, and atmospheric pressure. These factors can induce measurement drift, reduce sensitivity, and impair long-term sensor stability. Therefore, understanding and compensating for environmental influences are fundamental to achieving accurate and consistent gas detection in real-world battery monitoring applications [58 - 59].

### **9.2.1 Gas Sensors and Their Application**

Among the most widely employed gas sensors for detecting emissions associated with battery degradation are metal oxide semiconductor (MOS) sensors and electrochemical sensors. MOS sensors function on the principle of resistance variation, where adsorption of gas molecules such as hydrogen or ammonia onto the sensing surface alters the electrical resistivity of the

material. This mechanism grants MOS sensors high sensitivity and fast response times, making them suitable for detecting trace concentrations of degradation gases. However, their operation is highly dependent on environmental stability, particularly temperature and humidity, which can cause fluctuations in sensitivity and baseline drift.

Electrochemical sensors, in contrast, detect gases through redox reactions at an electrode–electrolyte interface, producing an electrical current proportional to the gas concentration. These sensors typically exhibit better stability in humid environments and are less affected by temperature fluctuations, although they often demonstrate lower sensitivity compared to MOS sensors. Consequently, the selection between MOS and electrochemical sensor technologies depends largely on the intended environmental conditions and the specific degradation gases of interest [50].

### 9.2.2 Environmental Factors Affecting Sensor Performance

Environmental conditions exert a profound effect on gas sensor performance, influencing both the accuracy and longevity of measurement systems. Temperature variations are among the most significant factors affecting sensor output. Elevated temperatures accelerate surface reactions in MOS sensors, potentially resulting in exaggerated readings or signal drift. Conversely, at low temperatures, adsorption kinetics may slow down, decreasing sensitivity and response speed. Electrochemical sensors are comparatively less temperature-sensitive but can still experience minor baseline shifts when exposed to substantial thermal fluctuations.

Humidity presents another critical challenge. Excess moisture can modify the surface chemistry of MOS sensors by forming water layers that interfere with gas adsorption processes. This interaction often leads to signal instability or even degradation of sensor performance over time. Electrochemical sensors, while more tolerant of moisture, can still experience performance degradation under prolonged exposure to high humidity, as electrolyte composition and electrode reactions may be altered.

Atmospheric pressure variations also influence gas sensor operation by affecting gas diffusion and concentration near the sensing surface. Pressure changes can lead to erroneous readings in enclosed systems, especially when diffusion rates are altered within the sensing chamber. To maintain accuracy, gas sensors used in such applications must be properly calibrated to compensate for pressure-dependent fluctuations [51].

### 9.2.3 Sensor Selection and Operational Considerations

The choice of gas sensor type is closely tied to the expected environmental conditions of operation. MOS sensors exhibit high sensitivity toward hydrogen and ammonia and are particularly effective for detecting early-stage degradation events in relatively dry environments. However, because of their susceptibility to temperature and humidity changes, they require careful thermal control and frequent calibration. Electrochemical sensors, on the other hand, offer greater operational stability across variable environmental conditions, particularly in systems exposed to fluctuating humidity and temperature. While they may provide slightly lower sensitivity than MOS sensors, their consistent performance and reduced need for recalibration make them advantageous for long-term, real-world battery monitoring applications.

In practical systems, the use of hybrid or multi-sensor configurations is increasingly common. These systems combine the advantages of different sensor types, allowing for cross-validation of gas concentration data and improved reliability under dynamic environmental conditions [16].

### 9.2.4 Calibration and Environmental Compensation

Calibration plays an important supporting role in maintaining the accuracy and reliability of gas sensors under varying environmental conditions. In the context of battery monitoring, environmental factors such as temperature, humidity, and pressure can significantly influence sensor response, leading to deviations between measured and actual gas concentrations. For example, metal oxide semiconductor (MOS) sensors operating at elevated temperatures (e.g., 35 °C with 60% relative humidity) may exhibit deviations of up to 5% due to thermal effects, whereas electrochemical sensors generally demonstrate greater stability with reduced signal drift under similar conditions.

To address these environmentally induced variations, compensation techniques are commonly incorporated into sensor systems. Temperature-compensated MOS sensors, for instance, can correct resistance changes caused by thermal fluctuations, improving measurement stability. In addition, modern gas sensing platforms often integrate environmental monitoring with adaptive correction mechanisms, allowing sensor outputs to be adjusted in response to changing ambient

conditions. These approaches enhance measurement reliability, particularly in dynamic operating environments such as battery systems [16].

While calibration methodologies are discussed in detail in Section 6. Gas Sensor Calibration, it is important to note here that environmental compensation forms a critical component of ensuring accurate sensor performance under real-world conditions. By accounting for external influences, these strategies enable more consistent and dependable gas detection for battery degradation monitoring.

### 9.2.5 Gaseous by Product of Battery Degradation

Different battery chemistries emit distinct gases as degradation progresses. Hydrogen ( $H_2$ ) is among the most common gases, generated by electrolyte decomposition and corrosion processes in both lithium-ion and lead-acid batteries. Ammonia ( $NH_3$ ) is typically produced during the degradation of lead-acid cells, whereas VOCs arise from the breakdown of organic electrolytes, separators, and polymeric binders in lithium-ion systems. Identifying and quantifying these gaseous by-products provide valuable insights into the underlying degradation mechanisms and enable the BMS to implement targeted preventive strategies. Monitoring such emissions not only aids in predicting battery lifetime but also enhances operational safety by signaling the onset of critical internal reactions that precede thermal or mechanical failure [52].

## 9.3 Approaches for In-Cell or Operando Sensing Relevant to Gas, Pressure, and Degradation in Batteries

Monitoring gas evolution, pressure changes, and degradation phenomena within battery cells is crucial for understanding their internal dynamics and ensuring safety. Several approaches have been developed for in-cell or operando sensing, focusing on detecting physical, optical, and chemical indicators of gas formation and degradation. These methods can be broadly classified into embedded pressure and strain sensors, optical fiber and interferometric sensors, electrochemical or chemical sensors, and hybrid headspace-based configurations.

### 9.3.1 Embedded Pressure, Swelling, and Strain Sensors

Embedded sensors that measure internal pressure, mechanical swelling, or strain are among the most mature technologies for in situ sensing within battery cells. Although these sensors do not directly detect gas molecules, they provide indirect but valuable information by monitoring the physical effects of gas buildup. For instance, a compact fiber-optic sensor combining a fiber structure with a micro-electro-mechanical element has been introduced for real-time monitoring of internal gas pressure in lithium-ion cells [37]. Similarly, differential electrochemical mass spectrometry (DEMS) has been compared with in situ non-dispersive infrared (NDIR) gas sensors to track gas evolution in commercial Li-ion cells, with the NDIR device positioned in the internal void or headspace rather than within the electrode stack [31].

Embedded sensors have also been applied to monitor temperature, strain, and pressure simultaneously inside commercial cells. A hybrid configuration combining fiber Bragg grating (FBG) and Fabry-Perot interferometer (FPI) sensors has demonstrated real-time tracking of internal temperature and pressure, correlating these parameters with external electrochemical performance. Comprehensive reviews have highlighted fiber-optic sensing methods for battery monitoring, emphasizing their ability to detect internal temperature and strain variations [53]. In addition, embedded sensing approaches for in situ measurement and safety monitoring have been reported, noting that detection often occurs only after pressure surpasses a critical threshold [53]. Overall, embedded pressure and strain sensors serve as valuable indirect indicators of internal gas generation, as gas formation typically manifests as increased pressure or swelling [53].

### 9.3.2 Optical Fiber, Absorption, and Interferometric Sensors

Optical fiber-based sensors and other spectroscopic optical systems are increasingly attractive for in situ battery monitoring due to their small size, immunity to electromagnetic interference, and capacity for multiplexed measurements. These sensors can probe local variations in gas concentration, refractive index, or optical absorption, even within confined cell volumes. Recent studies have reviewed advances in optical fiber sensing technologies for monitoring temperature, stress, and other internal parameters in batteries, including strategies for embedding optical fibers directly into cells [34]. In addition, advanced optical fiber sensors

have been explored for detecting micro-level structural, chemical, and safety-related changes such as electrolyte degradation or interfacial evolution providing deeper insights into internal battery states [34].

Interferometric and Fabry-Perot cavity designs have been proposed to detect refractive index variations caused by gas or pressure changes. Although many such systems have been demonstrated outside the battery environment, their miniaturized designs indicate strong potential for future internal applications. For example, distributed fiber Raman systems for hydrogen detection, based on stimulated Raman spectroscopy, have been proposed as external prototypes that may eventually evolve into internal miniaturized gas sensors. Despite their promise, challenges remain in achieving high sensitivity within the narrow and reactive environments of battery cells, particularly in ensuring that optical paths can effectively interact with gas phases or void regions without disturbing electrochemical components [53].

### 9.3.3 Electrochemical and Chemical Sensors within Electrolytes or Interfaces

An alternative route for in situ sensing involves electrochemical or chemical sensors that monitor dissolved intermediates, gaseous precursors, or chemical indicators such as pH and redox-active species within the electrolyte. These sensors do not directly detect gaseous molecules but instead sense chemical species related to gas formation or degradation processes. Recent studies (2025) have demonstrated in situ electrochemical detection of pH and dissolved oxygen within rechargeable zinc-based batteries, marking progress toward real internal chemical sensing [54].

Conventional gas sensors such as amperometric or potentiometric types rely on redox reactions of gas molecules at sensor electrodes to produce measurable currents. However, embedding such sensors within a working battery is challenging due to competing electrochemical reactions, electrolyte interference, and electrode polarization. Consequently, fully integrated electrochemical gas sensors remain rare. Nevertheless, as protective materials and interface engineering advance, the feasibility of incorporating such sensors directly into battery environments is expected to improve.

### 9.3.4 Hybrid and Internal Headspace Sensor Configurations

Given the practical difficulties of embedding gas sensors directly within the electrode stack, hybrid configurations that place micro-sensors in internal voids or headspaces of sealed cells have gained attention. These sensors can monitor gas evolution within the enclosed cell environment while avoiding direct contact with the liquid electrolyte. For example, the IEST GVM2200 in situ battery gassing volume analyzer provides a commercial solution for measuring gas evolution through monitoring volume changes, internal pressure, and even gas composition in confined headspaces primarily for research and development rather than permanent cell integration [52].

Similarly, various studies presented at SPIE conferences have described in situ setups for detecting gas generation within internal battery volumes. Other work focusing on “In situ measurement of internal gas pressure” has involved embedding pressure sensors into internal layers or cell casings. Such hybrid systems provide a practical bridge between fully external gas analysis and fully embedded in-cell sensors, offering valuable insight into gas evolution and cell degradation mechanisms while maintaining experimental flexibility.

## 9.4 Characterization of Evolved Gas Species in Batteries

In the context of battery degradation and safety diagnostics, identifying and quantifying gaseous species generated during electrochemical cycling or under abusive conditions is of critical importance. The gases of interest primarily include hydrogen ( $H_2$ ), carbon monoxide (CO), and carbon dioxide ( $CO_2$ ), which are among the most common byproducts of electrolyte decomposition and electrode–electrolyte side reactions in lithium-ion batteries. In addition, hydrocarbons and light organic species such as methane ( $CH_4$ ), ethylene ( $C_2H_4$ ), and other volatile organic compounds are frequently observed, typically arising from reductive decomposition of carbonate-based electrolytes or solvent breakdown during overcharge and high-temperature operation [65]. Fluorinated species, most notably hydrogen fluoride (HF), also emerge in systems that employ fluorinated salts such as  $LiPF_6$ ; HF formation is particularly concerning due to its corrosive nature and its ability to catalyze further electrolyte and electrode degradation [31]. Under abusive or failure conditions, gases derived from oxygen evolution or other oxidative processes may also be released, especially from cathode materials with high

oxygen content such as layered oxides (e.g.,  $\text{LiNi}_x\text{Mn}_y\text{Co}_z\text{O}_2$ ), contributing to the onset of thermal runaway [66]. Moreover, dissolved intermediates or radical species generated transiently within the electrolyte may subsequently evolve into gaseous forms, offering early indicators of degradation pathways before visible failure occurs [65]. Ideally, an in-cell gas sensor should therefore possess sufficient selectivity and sensitivity to detect one or more of these species at very low partial pressures, allowing for real-time insight into electrochemical stability, degradation mechanisms, and the early warning of potential safety hazards within the cell [55].

## 9.5 Summary and Implications

Environmental conditions including temperature, humidity, and atmospheric pressure play a decisive role in determining the precision, stability, and lifespan of gas sensors used for monitoring battery degradation. MOS sensors, though highly sensitive to key degradation gases such as hydrogen and ammonia, exhibit pronounced dependence on environmental stability and thus demand frequent recalibration and environmental control. Electrochemical sensors, in contrast, maintain more consistent performance across a wider range of environmental conditions, though they generally offer lower sensitivity. Optimal sensor performance depends on proper selection, calibration, and operational configuration tailored to the intended environment.

Looking ahead, advances in in situ and operando sensing technologies are paving the way for the direct integration of gas sensors within battery architectures. Embedding sensors inside cells allows real-time tracking of gas evolution, internal pressure changes, and chemical transformations during battery operation. Such integrated monitoring systems hold immense potential for improving safety, extending service life, and advancing the sustainability of next-generation energy storage technologies [51].

## 9.6 Challenges and Future Research Directions in Gas Sensor-Based Degradation Monitoring of Lithium-Ion Batteries

Despite significant advances in battery diagnostics, the integration of embedded gas and composition sensors within lithium-ion cells remains a substantial challenge, primarily due to a combination of technical, chemical, and practical limitations that have so far restricted such approaches to research prototypes rather than commercial deployment. One of the most critical issues is sensitivity and signal detection threshold: gas generation within cells is often negligible until substantial degradation or failure begins, requiring sensors capable of detecting extremely small changes in gas concentration or pressure within confined volumes an inherently difficult task in sealed electrochemical systems [66]. Furthermore, chemical stability and compatibility of sensing elements pose additional barriers, as sensors must withstand harsh electrolytes, solvents, decomposition products (e.g., hydrofluoric acid from  $\text{LiPF}_6$  breakdown), and high electrochemical potentials over extended cycling without performance loss or chemical interference [67]. Another persistent difficulty lies in achieving non-invasiveness, since the sensor must operate without disrupting the battery cell's performance, provoking local current disturbances, acting as an unintended electrode, or otherwise altering the electrochemical or thermal stability of the cell. Compounding these problems, spatial resolution remains limited because bulk sensors such as pressure or strain gauges typically reflect only global changes and cannot accurately localize gas generation or identify which internal regions are contributing to degradation; likewise, gas-composition sensors require a defined path for gas diffusion to the sensing zone, which is hard to achieve without altering the cell structure [56]. Long-term reliability also depends on calibration stability, as drift, baseline shifts, sensor ageing and degradation across hundreds or thousands of charge–discharge cycles can obscure true signals if not effectively compensated [66]. In addition, integration and manufacturing constraints continue to impede progress: embedding sensors into practical battery formats such as pouch, prismatic or cylindrical cells at scale poses substantial engineering challenges, particularly in maintaining hermetic sealing, sensor integrity, and electrical connectivity under repetitive mechanical and thermal stresses [68]. Finally, even when reliable measurements are obtained, data interpretation and modelling remain nontrivial, as correlating pressure or concentration variations to specific gas-generation rates or degradation pathways requires complex multiphysics models and well-calibrated experimental frameworks [67]. Collectively, these interrelated obstacles spanning sensitivity, chemical robustness, non-invasiveness, spatial resolution, calibration, manufacturability, and interpretability explain why most embedded gas-

sensing techniques for lithium-ion batteries remain at the laboratory stage, underscoring the need for continued interdisciplinary research in sensor design, electrochemistry, and data analytics to enable reliable in-situ diagnostics for next-generation energy storage systems.

## 10 Conclusion

The integration of commercial gas sensors into Battery Management Systems (BMS) represents a major step toward achieving safer, more reliable, and longer-lasting energy storage technologies. While conventional BMS architectures rely primarily on voltage, current, and temperature data, the inclusion of gas concentration measurements provides an additional safety layer capable of detecting early signs of electrolyte decomposition, gas release, and other chemical degradation processes. By feeding real-time gas-sensing data into the BMS, it becomes possible to identify abnormal reactions before thermal runaway, adjust charging and discharging parameters to mitigate stress, and implement predictive maintenance strategies that extend battery life and enhance operational safety across applications such as electric vehicles, grid-scale storage, and portable electronics.

Battery degradation whether in lithium-ion, lead-acid, or nickel–metal hydride systems is driven by electrochemical reactions such as SEI growth, sulfation, lithium plating, and material fatigue, as well as by thermal and mechanical stresses. These processes cause capacity loss, reduced power output, safety hazards, and shortened cycle life. Monitoring through advanced BMS technologies is therefore essential, employing not only conventional electrical sensors but also complementary diagnostic methods such as electrochemical impedance spectroscopy (EIS), thermal sensors, and AI-based predictive models. Within this framework, gas sensors play a particularly valuable role by directly identifying the chemical by-products of degradation, including gases such as O<sub>2</sub>, CO<sub>2</sub>, CO, H<sub>2</sub>, and volatile organic compounds (VOCs), which serve as early indicators of internal failure mechanisms.

Commercial gas-sensing technologies operate on several physical and chemical principles, including resistance variation in metal-oxide semiconductors (MOS), redox current generation in electrochemical cells, infrared absorption (NDIR) for CO<sub>2</sub>, and thermal conductivity for hydrogen detection. Each technology involves practical trade-offs: MOS sensors are low-cost and sensitive but suffer from limited selectivity and stability; optical sensors provide high selectivity and robustness but at greater cost and power consumption. Emerging research trends are moving toward hybrid and nanostructured materials, in-situ fiber-optic sensing, and AI-enhanced sensor arrays that combine multiple detection mechanisms to achieve improved reliability, selectivity, and long-term stability under real-world operating conditions.

The adoption of gas sensors within BMS architectures not only enhances safety but also contributes to sustainability by extending battery lifespan, improving efficiency, and reducing material waste. Continuous advancements in sensor miniaturization, materials engineering, and data fusion are accelerating the transition from laboratory prototypes to commercially viable, integrated solutions. Ultimately, gas-sensor-enabled BMSs offer a pathway toward intelligent, self-aware, and environmentally responsible battery systems capable of supporting the rapid expansion of electrified transportation, renewable energy storage, and next-generation smart devices.

Gas sensing technologies have made impressive strides in recent years, offering valuable insights into degradation processes inside electrochemical cells. However, several key challenges continue to limit their transition from lab-scale prototypes to commercial adoption. Sensors must detect extremely low levels of gas generation, often long before failure becomes visible, all while operating in chemically harsh and confined environments. They also need to be non-invasive, avoiding any impact on the cell's performance, and offer enough spatial resolution to pinpoint where gases are forming not just that they are. Long-term stability, calibration drift, and reliable signal interpretation over thousands of cycles add further complexity. On top of this, integrating sensors into real-world cell formats like pouches, prismatic, or cylindrical cells at scale remains a significant hurdle.

Despite these challenges, the growing understanding of these issues and the increasing collaboration across materials science, sensor engineering, and data modelling offer a promising path forward. Bridging the gap between research and application will require continued innovation, but the potential impact on battery safety, performance, and lifetime makes it a goal well worth pursuing.

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