


Challenges and opportunities for high-quality battery production at scale

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As the world electrifies, global battery production is expected to surge. However, batteries are both difficult to produce at the gigawatt-hour scale and sensitive to minor manufacturing variation. As a result, the battery industry has already experienced both highly-visible safety incidents and under-the-radar reliability issues—a trend that will only worsen if left unaddressed. Here we highlight both the challenges and opportunities to enable battery quality at scale. We first describe the interplay between various battery failure modes and their numerous root causes. We then discuss how to manage and improve battery quality during production. We hope our perspective brings greater visibility to the battery quality challenge to enable safe global electrification.

We currently live in exciting times for the battery industry. In light of the increasingly visible impacts of climate change¹, consumer, corporate, and governmental support for electric vehicles (EVs) and stationary energy storage is crescendoing^{2,3}. The industry is projected to grow by 30% per year until 2030⁴. A planetary-scale energy transition is well underway, requiring unprecedented volumes of battery-powered energy storage.

However, the global battery production ramp is threatened by looming challenges. While concerns around the materials supply chain and the “valley of death” for new battery concepts are now well-established^{5,6}, we highlight an equally important but less frequently discussed risk: poor battery quality and its impacts on battery safety, reliability, and the financial success of cell manufacturing (Fig. 1). Indeed, since the commercialization of lithium-ion battery technology in 1991^{7,8}, several high-profile safety events (Fig. 1a) have occurred in sectors such as consumer electronics, electric micromobility, EVs, aviation, and medical devices^{9,10}. One infamous EV safety case required a USD \$1.9B fleetwide recall^{11,12}. Unfortunately, as applications of battery technology have proliferated, the incidence rate of catastrophic events appears to be increasing: for instance, hundreds of electric bike fires have occurred over the past few years in New York City alone, triggering legislation¹³. Underestimating these battery safety risks will have devastating financial, human, and environmental costs and jeopardize consumer and regulatory confidence in battery technology.

Aside from headline-grabbing safety events, battery quality issues can have outsize impacts on the reliability of battery-powered devices (Fig. 1b). For instance, an EV pack typically consists of hundreds or thousands of cells arranged in series and in parallel, often combined

into modules. (Although we focus on EVs in this article, these principles apply to any battery-powered device). These configurations determine the sensitivity of the pack to cells that exhibit either open-circuit failure, short-circuit failure, or even heterogeneity. A cell that exhibits open-circuit failure will cause all cells connected to it in series to become inoperable (similar to series-connected Christmas tree lights)^{14–16}. A cell that exhibits short-circuit failure will cause all cells connected to it in series to overcharge¹⁷ and cause all cells connected to it in parallel to discharge into it in order to maintain the same voltage^{14,17}—not to mention the risk of short-induced thermal runaway propagating to neighboring cells^{18–20}. Additionally, but less critically, variability in initial cell energy and cell aging can cause a pack to underperform relative to an otherwise identical pack with no cell-to-cell variability^{21–23}. While these issues can be partially managed by hardware- and software-based pack balancing strategies, these approaches add mass and complexity to pack design and are often insufficient to manage severe issues^{15,16}. In summary, the failure of a single cell can cause complete pack failure.

The core challenge underlying these safety and reliability issues is the unforgiving requirements of battery production at scale (Fig. 1c): namely, high production yields and throughputs along with extreme tolerance and purity specifications. A large Western 38 GWh/year battery gigafactory produces six million cylindrical cells per day—or nearly 70 cells per second²⁴. Simultaneously, modern batteries must be manufactured to geometric tolerances on the order of a few microns while avoiding a host of similarly-sized particle contaminants^{25–27}. Ensuring that each cell meets these specifications while being manufactured at high rates across multiple production lines that are

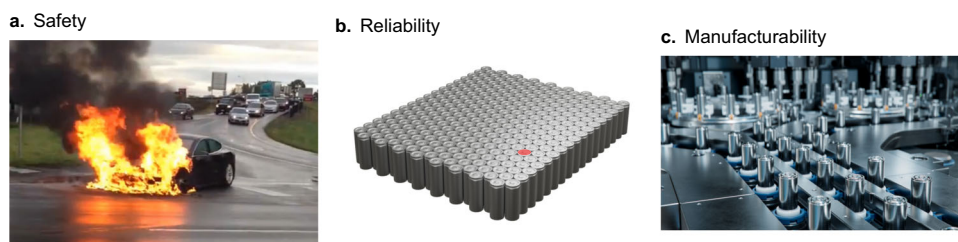


Fig. 1 | Three challenges related to poor battery quality. **a** Safety events, in which a single battery defect can cause harm to humans or the environment. **b** Pack/device reliability, in which a single cell can cause an entire pack or device to fail. Failure within warranty will require replacement at the expense of the

manufacturer. **c** Manufacturability, or the immense difficulty of producing batteries at scale profitably (i.e., with high yield, throughput, and ramp-up time) while maintaining high quality (i.e., while maintaining high purities and tight tolerances).

continuously modified, maintained, and upgraded is a colossal task^{6,24,28}. Thus, quality control is a key differentiator between top-tier and bottom-tier cell producers. Ultimately, given the inevitable quality obstacles faced during large-scale battery production, both cell producers and original equipment manufacturers (OEMs; in this context, the manufacturers of any battery-powered device) must learn to understand and manage this issue.

Based on our experiences in the battery industry, we believe ensuring battery quality at scale is perhaps the most important technical challenge hindering the ability to rapidly ramp battery production in the years to come. Yet a comprehensive framework and vision for quality in the battery industry is in its infancy. In this perspective, we share our outlook on the challenges and opportunities for enabling battery quality at scale. First, we define battery quality and its relationship to other key attributes such as lifetime, failure, safety, reliability, and manufacturing performance. We then outline the difficult options available for managing and improving battery quality during cell production. We hope our perspective sheds light on this critical challenge and catalyzes a broader acceptance of its importance for an electrified future.

Defining key attributes related to battery quality

Fundamentally, the challenge of ensuring battery quality is driven by the complexity of battery performance. An especially important, sensitive, and complex pillar of battery performance is battery lifetime and failure. While our collective understanding of this topic has continued to grow, we also continue to learn how complex and interdependent battery lifetime and failure can be^{29–31}. Note that although we focus on lithium-ion batteries throughout this perspective, these principles generally apply to all electrochemical batteries (e.g., lithium-ion, lithium-metal, sodium-ion, and more; aqueous and non-aqueous; primary and secondary).

In Fig. 2, we present a taxonomy of battery failure. We first list influential factors that drive battery failure (Fig. 2a). We define three categories of battery failure, ordered by severity: performance degradation (Fig. 2b), functional failure (Fig. 2c), and safety events (Fig. 2d). We discuss key terms and concepts embodied in this figure in the remainder of this section.

Classifying battery failure and defining key terms

We begin by describing three broad classifications of battery failure and define key concepts along the way.

First, we discuss performance degradation (Fig. 2b). In battery devices, the available energy and other performance aspects such as rate capability decrease over time. Generally, the root causes of performance degradation are electrochemical and chemical degradation modes (subsequently referred to as “electrochemical” for simplicity) and have been the focus of much of the literature on battery lifetime^{29–34}. Two classic electrochemical degradation modes include

solid-electrolyte interphase growth^{32,35–37} and cathode-electrolyte interface growth³⁸, both of which decrease battery capacity and energy and increase cell internal resistance. Another significant performance degradation mode is active material loss from the positive and negative electrodes, in which electrode host sites become inaccessible for lithium ions^{39,40}. However, many subtle effects, including current collector corrosion^{41,42} and “crosstalk” between the electrodes^{43,44}, can also contribute^{30,31}.

All batteries experience performance degradation to some degree, and minimizing its extent is critical to improve battery sustainability and to bring next-generation battery chemistries to market⁴⁵. Furthermore, the long duration of electrochemical lifetime testing is a major bottleneck to innovation in battery technology^{46,47}. However, energy retention can be optimized to a remarkable extent today, as demonstrated by the Dahn lab’s work on “million-mile batteries”⁴⁷ and beyond⁴⁸. Overall, while performance degradation is certainly a key element of lifetime and failure, this category of battery failure does not threaten global electrification efforts to the same extent as the two categories that follow.

A second category of battery failure, subsequently termed functional failure (Fig. 2c), is a broader class of failure that renders the cell unable to meet its functional requirements. In other words, the cell becomes inoperable or, at minimum, exhibits severely diminished utility. Broadly, open-circuit and short-circuit failures are two major classes of functional failure. In a cell context, open-circuit failure refers to a cell with a broken electronic pathway (very high resistance), and short-circuit failure refers to a cell with an inadvertent electronic connection between the electrodes (very low resistance). These failure modes are internal to the cell. Unlike most cases of performance degradation, these two issues can render the cell and/or pack entirely inoperable. For instance, an internal short can inhibit charging and impact pack balancing^{14,16,17}. In these cases, failure is often more clear but still arbitrary (e.g., what short-circuit current should be considered failing?). We discuss the root causes of these failure modes in detail in the “Battery quality” section.

Performance degradation is often codified as a functional failure by specifying limits for its extent. For instance, some commonly cited limits for energy retention in publications and EV warranties are 70%⁴⁹ or 80%⁵⁰. Of course, these limits are arbitrary, as a battery is only marginally less useful with 79.9% energy retention than with 80.1% energy retention. Conventionally, the terms “battery lifetime”, “cycle life”, and “calendar life” implicitly refer to functional requirements related to performance degradation. For example, a calendar life requirement might be that a cell retains 80% of its energy over a period of eight years. Severe electrochemical events, such as a “knee” in capacity or energy retention³³ (i.e., when the capacity/energy suddenly decreases) or an “elbow” in internal resistance³⁴ (i.e., when the internal resistance suddenly increases), are major threats to meeting these functional requirements. Avoiding knees and elbows may also be

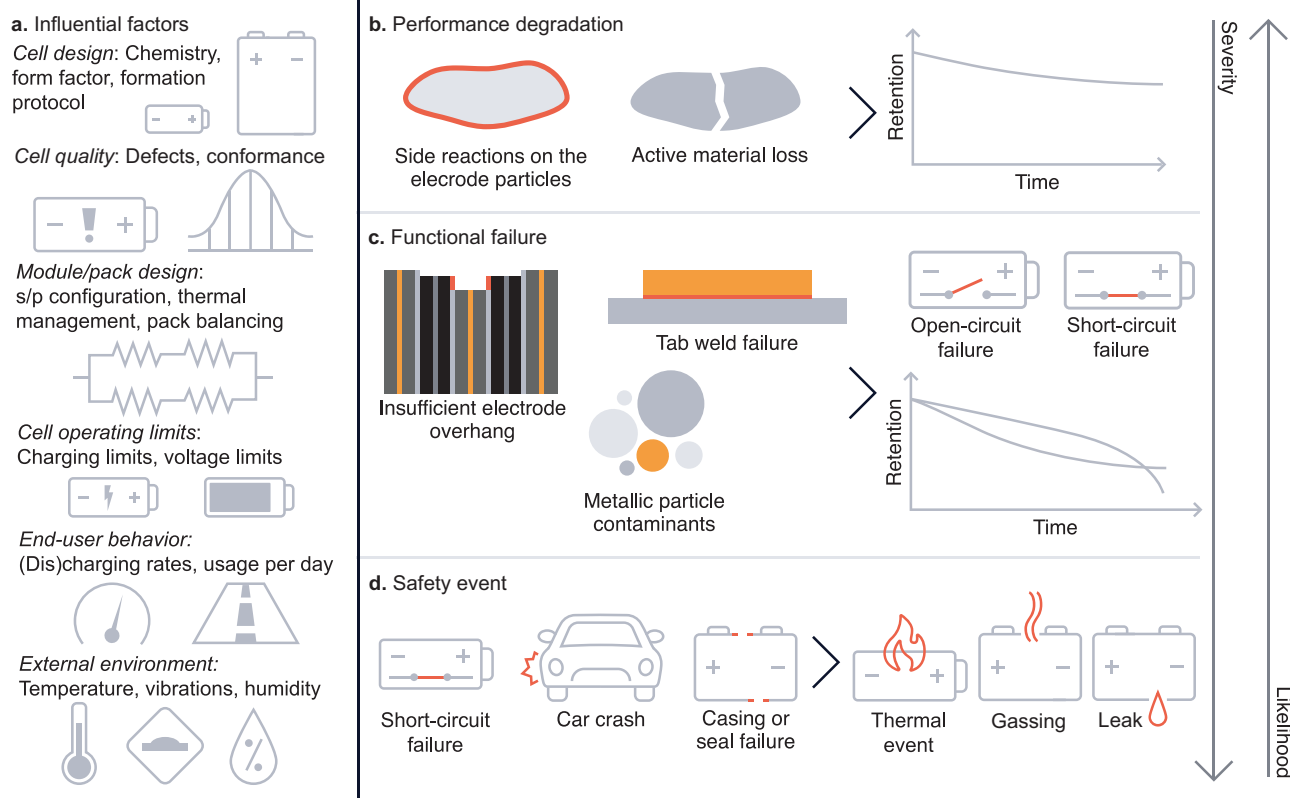


Fig. 2 | A taxonomy of battery failure. **a** Factors that influence battery lifetime and failure. The cell producer or OEM can control some of these factors but not all. **b–d** Three categories of battery failure, in increasing order of severity and decreasing order of likelihood (from top to bottom). These three categories of failure influence and interact with each other. **b** Performance degradation. Performance degradation is often caused by (electro)chemical side reactions that consume lithium or inactivate electrode material, resulting in diminished cell

performance. **c** Functional failure. Functional failures are often caused by electrochemical, mechanical, or contamination issues (e.g., lithium plating, weld failure, and metallic contaminants) that cause cells to exhibit open-circuit failure, short-circuit failure, or severely diminished performance. **d** Safety events. Safety events can be initiated by a variety of root causes, most notably internal shorting but also external initiation events (e.g., a car crash) and casing/seal failure⁶², and result in an event that harms the health of humans and/or the environment.

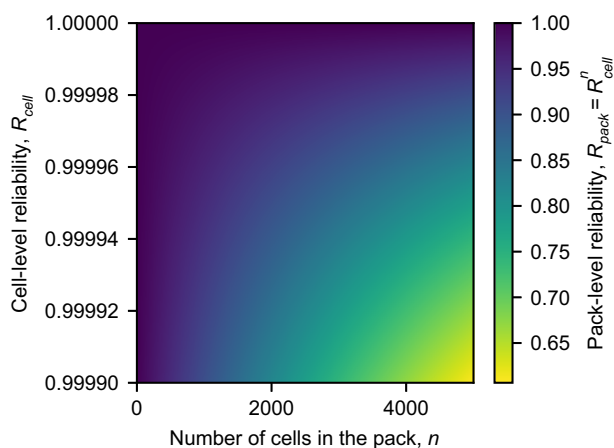


Fig. 3 | The relationship between cell-level reliability and pack-level reliability. Here, we assume that the failure of a single cell causes the failure of the entire pack; the validity of this assumption depends on the type of failure, the pack architecture, and other factors^{14,20}. Under this assumption, the pack-level reliability is given as $R_{pack} = R_{cell}^n$, where R_{pack} is the pack-level reliability, R_{cell} is the cell-level reliability, and n is the number of cells in the pack. While this visualization may suggest that packs with smaller numbers of cells are more reliable, we note that R_{cell} may be lower for higher-energy cells (which are needed to build an equivalently-sized pack).

considered functional requirements in their own right, as they can lead to user frustration relative to graceful failure scenarios⁵¹ (i.e., when the performance of the battery slowly diminishes until the device is replaced) and are often correlated with other functional failures (e.g., lithium plating may be a root cause of both knees and internal shorting^{33,52}).

A key term in discussing functional failures is reliability, which is defined as how well a product can perform its intended functions given a specified set of operating conditions and a specified period of time⁵³. Thus, “battery reliability” can be defined as how well a battery avoids functional failure over its desired operating lifetime given a set of operating conditions. As previously discussed, single-cell reliability is a key determinant of pack reliability. We illustrate how single-cell reliability translates to pack-level reliability in Fig. 3. Reliability science is well-established⁵⁴ and can help practitioners empirically test for functional failure modes^{55,56}, but the large number of operating conditions, wide variety of failure modes, and high lifetime requirements make battery reliability testing challenging. While accelerated testing (e.g., high temperature or fast cycling)^{50,57} and early prediction techniques (e.g., physics- or data-driven techniques)^{46,58} can help reduce the cost of reliability testing, the discrete, latent nature of many functional failures (e.g., a sudden tab weld failure⁵⁹) sets a lower bound on the cost reduction. In other words, testing for “threshold” failure mechanisms³³ for which the threshold is unknown (i.e., when the tab weld will fail) is, by definition, limited by the time it takes to identify the

threshold. Similarly, electrochemomechanical interactions between performance degradation and functional failures (e.g., gassing due to side reactions and/or electrode swelling^{33,60,61}) can necessitate long testing times.

The most severe category of battery failure is safety events (Fig. 2d). Here, we define a safety event as any battery issue that could cause harm to humans or the environment. With this definition, fires and explosions induced by thermal runaway are perhaps the most vivid and catastrophic issues, but the release of toxic gas via a gassing event¹⁰ or the release of toxic liquids via a leak^{18,62} would also qualify. Of course, battery safety events can cause life-threatening injury and are currently a hot-button issue among legislators and regulators¹³.

As many excellent reviews of battery safety have been published^{10,18,20,63}, we provide a cursory review here. In general, thermal runaway can have extrinsic or intrinsic triggering mechanisms. Extrinsic triggering mechanisms include electrical (e.g., overcharge), thermal (e.g., sudden rise in environmental temperature), and mechanical (e.g., a vehicle crash) mechanisms. Zhang et al.⁶⁴ and Lai et al.⁶⁵ have comprehensively reviewed the most significant intrinsic triggering mechanism, internal short-circuiting, which can lead to excess internal heat generation and thus initiate a combustion event. However, internal shorting is not the only triggering mechanism for runaway; localized current increases (e.g., from tab tears) can create thermal hotspots⁵⁹, and Liu et al.⁶⁶ reported a thermal runaway mechanism driven by crosstalk. Note that aged cells with performance degradation in the absence of lithium plating generally exhibit less severe thermal runaway^{60,67}. Thus, safety events are often linked to performance degradation and (especially) functional failures. The time between the initiation of a functional failure such as an internal short and the initiation of a safety event such as a runaway can vary significantly^{52,64,65}.

A major factor in battery design is the extent of the safety margin for both intrinsic and extrinsic triggering mechanisms. For instance, separators are often designed with safety considerations such as shutdown temperature in mind⁶⁸, and the wall thickness of the casing can be tuned for resistance to side rupture and external mechanical initiation events⁶⁹. Safety concerns also influence module and pack design^{18,19}. This safety factor must consider the application; for instance, pacemaker batteries should be designed with a large safety margin on principle, while a grid storage installation intended to operate far from human habitation may require a less strict safety margin. These design choices often require tradeoffs between cell performance (e.g., energy density and rate capability), safety margin, and cost.

The large variety of driving forces for battery failure (Fig. 2a)–and their interactions–adds another dimension to this challenge. We review these factors in Supplementary Discussion 1. Overall, the wide range of factors that influence battery lifetime and failure, coupled with the wide range of failure modes, leads to hundreds or even thousands of risk factor-failure mode combinations to consider. Cell producers and OEMs can control some of these risk factors (e.g., cell design and cell operating limits) but not all (e.g., end-user behavior and cell operating environment). A deep understanding of both end-user behavior (distributions and the most extreme behaviors) and the environmental conditions introduced by end users can enable OEMs to better estimate warranty liabilities caused by these external risk factors. Here, field telemetry can play a crucial role⁷⁰.

Battery quality

One of the most influential factors for battery lifetime and failure is battery quality, which underlies our entire discussion thus far. We define battery quality via one of two definitions: (a) defect rate and (b) conformance.

First, we define battery quality via defect rate. Generally speaking, a poor-quality product has a high rate of manufacturing defects. We

previously discussed how battery defects cause functional failures (typically open-circuit or short-circuit failure) or safety events immediately or in use. While some of these defects are obvious, many are subtle and only manifest under special conditions. For instance, the Chevrolet Bolt's safety issues were attributed to the simultaneous presence of a torn negative electrode and a folded separator¹¹. Cells with poor material quality that are otherwise well-built can also be considered defective (e.g., corrosion)⁷¹. In reality, a cell's survival is threatened by dozens of failure modes.

As shown in Fig. 4, a large ensemble of battery defects can cause either open-circuit (Fig. 4a) or short-circuit (Fig. 4b) failure. In general, open-circuit failure is most likely to occur at the most prominent components of the electronic pathway of the cell. For instance, a failure of the weld between the tab and the terminal, a tab tear, and corrosion can all lead to open-circuit failure⁵⁹. Furthermore, some cell safety devices, such as current interrupt devices, can intentionally cause open-circuit failure upon activation⁷². In contrast, because short-circuit failure can occur at any location where the positive and negative electrodes are in electronic contact, any number of subtle, micron-scale imperfections can lead to short-circuit failure. A classic example is lithium plating, in which lithium-metal dendrites puncture the separator and create an electronic connection between the electrodes^{52,73}. While plating can occur for a number of reasons, a local region where the ratio of negative electrode to positive electrode capacity ("N/P ratio") is less than one is often responsible^{33,52,73}. This condition can occur due to electrode "overhang" issues during winding or stacking as well as electrode coating defects^{52,74–76}. Beyond plating, any number of mechanical imperfections can induce an internal short. Metallic particle contaminants, often only tens of microns in diameter, can either cause a direct short between the electrodes via separator puncture or induce metal deposition on an electrode, which can subsequently develop into a short^{26,27,76}. Finally, many other defects such as separator pinholes, separator misalignment, folded separators, electrode wrinkles, jellyroll buckling, metallic burrs or tears on current collectors or tabs, and overlapping tabs can induce an internal short-circuit^{11,59,61,64,65,76}. Thus, internal short circuits are of particular concern in the battery industry due to the abundance of micron-scale root causes and their severity^{64,65,76}.

Critically, many of these defects are latent defects, meaning they are initially present but dormant and may activate at some point in life. By definition, latent defects have no electrochemical signature until the defect manifests into failure (e.g., an internal short); in fact, even an internal short may not be detectable until its magnitude develops beyond some critical value (i.e., the point at which this localized electrochemical signal is significant enough to be detected despite the health of the rest of the cell). We illustrate this concept in Supplementary Fig. 1. Not unlike a malignant tumor, a small defect may cause premature failure for an otherwise entirely healthy cell (i.e., a cell with minimal performance degradation). This process can be thought of as a "threshold" mechanism³³, where failure occurs once some aspect of the cell's internal state has crossed some threshold. These threshold failure mechanisms can be driven by a multitude of forces (e.g., electrochemomechanical electrode swelling, gassing due to side reactions, and/or stress on a critical component) which are generally related to performance degradation mechanisms^{60,61,77,78}. Both the rate of change for the internal state and the magnitude of the threshold will vary based on the previously discussed factors, namely cell design, cell quality, module/pack design, cell operating limits, end-user behavior, and environmental conditions.

The key metric for this definition of battery quality is defective parts per million (DPPM)⁷⁹. However, many subtleties can make DPPM quantification difficult, if not impossible. First, developing a comprehensive understanding and precise definition of all possible defects is challenging, especially given the aforementioned interactions between factors for battery failure as well as the interactions between defects

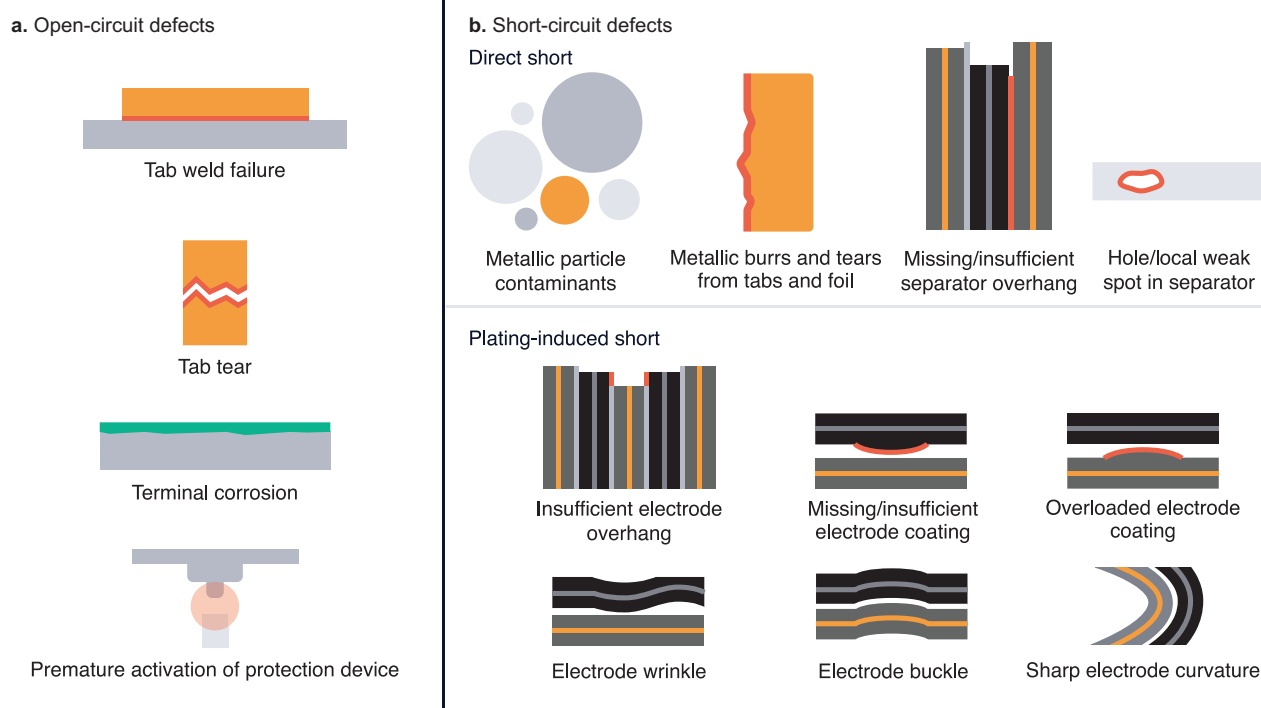


Fig. 4 | Common battery defects that can cause functional failures. These defects can cause **a** open-circuit failure and **b** short-circuit failure and can manifest either during manufacturing or, in the case of latent defects, over life. The relevant

length scale for most of these defects is 10–100 μm . The defects depicted here are far from exhaustive.

themselves¹¹. For example, defective cells that may fail for one end user may not fail for another end user based on differences in their behavior. Second, many of these defects are latent, which means they can be difficult to detect in production. Third, some fraction of these defects will escape the production line simply due to imperfect detection techniques and sensitivities.

Counterfeit cells are perhaps an extreme case of defectiveness, in which standard safety features are deliberately removed to reduce weight and cost⁷¹. Counterfeit cells of course often have very poor quality, and many of the highly-publicized battery safety events discussed previously are a result of low-quality and/or counterfeit batteries^{10,13,71}.

We now consider a second definition of battery quality: conformance. Conformance refers to how well a manufactured product conforms to its design²⁵. The battery industry often refers to non-conformance as “cell-to-cell variability”^{22,55,56,80}. Conformance is a broader definition of cell quality than defect rate in that defects are one instance of nonconformance from the intended design. In general, conformance is a function of process and quality control. Beck et al.⁸⁰ reviewed the primary drivers of nonconformance in batteries and battery production.

Lack of conformance to the design may not directly cause battery failure; for instance, a key quality indicator such as the distribution of cell energy may be larger than desired but still fall within an acceptable band. That said, poor conformance generally indicates poor process control, which indicates that a production line is at a higher risk of producing defective cells. Furthermore, even in the absence of cell-level defects, poor conformance can directly influence failure in at least two significant ways.

First, all three categories of battery failure are often highly sensitive to small differences in cell structure and composition, so small deviations may result in a significant increase in the likelihood and severity of failure and thus higher warranty exposure^{22,33,55,81,82}. For

instance, some proposed knee pathways exhibit superlinear sensitivities to small variations in percolation network connectivity or electrolyte additive concentration³³. The aforementioned Chevrolet Bolt safety issue only occurred when two rare defects were present in the same cell¹¹. Thus, even a mild degree of poor conformance can have dramatic impacts on battery lifetime and failure. On a related note, cell testing for performance degradation, functional failures, and safety is more expensive with higher cell-to-cell variability since more cells are required for testing to draw meaningful conclusions^{81–83}. Finally, poor conformance makes root-causing test and field failures more difficult and expensive, as cell quality adds yet another set of complex factors to untangle.

Second, a high degree of cell variability within a module or pack has several intertwined impacts on pack behavior. This issue may prevent the pack from meeting its requirements (e.g., energy or rate capability) since packs are generally limited by their weakest cell^{16,23,56}. In other words, all else being equal, a pack with high variability in cell energy will have lower effective energy than a pack with low variability in cell energy. Cell variability can also cause voltage or current imbalance, which further limits performance and can cause pack-level failure as previously discussed^{14,16,17,56}. Finally, these imbalances can cause heterogeneous aging under certain conditions, i.e., a cell with low energy may experience a higher effective C rate relative to a nominal cell^{56,84,85}.

In summary, both senses of battery quality (defectiveness and conformance) are critical determinants of battery failure and thus the financial success of cell and EV production endeavors. We revisit battery quality in the “Managing battery quality in production” section.

Manufacturing performance

Ultimately, of course, a business cannot build and operate a multi-billion-dollar battery factory without a return on its investment. This return is determined by several cell production indicators, such as

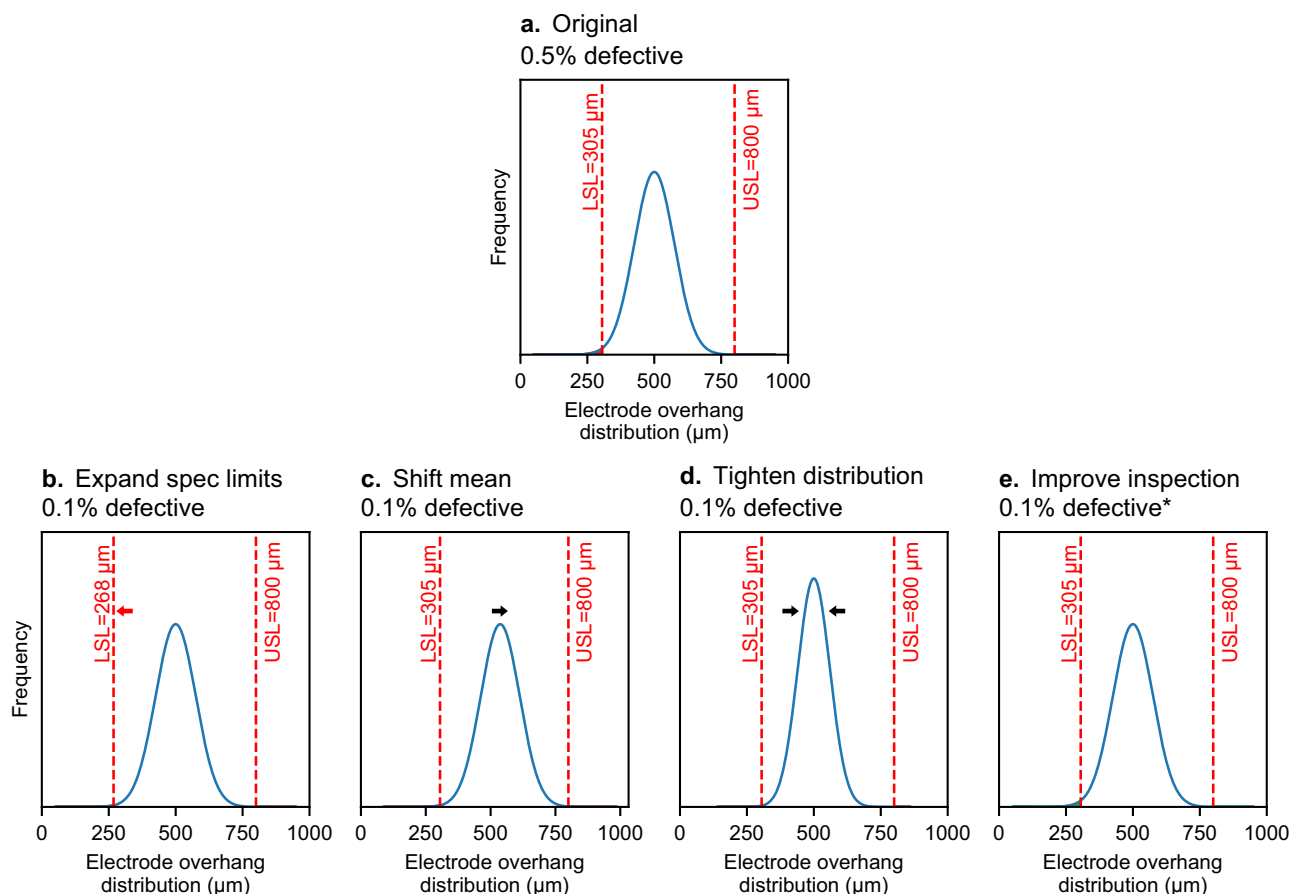


Fig. 5 | Pathways for improving battery quality control. We use electrode overhang as an illustrative example of a battery quality metric. **a** The distribution of electrode overhang for a population of cells, modeled as a Gaussian distribution. The vertical lines represent the lower specification limit (LSL) and upper specification limit (USL), although note that some requirements may only have one of these specification limits. In this example, a fraction (0.5%) of the population falls below the LSL and is thus out of spec. Cell producers can consider four pathways

for managing battery quality: **b** expanding the specification limits, **c** shifting the population mean, **d** tightening the distribution, and/or **e** improving inspection. For improved inspection, the 0.1% defect rate assumes an inspection approach in which defective cells do not escape the factory. Note that a defect rate of even 0.1% is much too high (see Fig. 3) but exaggerated for illustration. The parameters used to generate these distributions are provided in Supplementary Table 1.

capital expenditures, operating expenses, yield, ramp-up time, utilization, throughput, profitability, and the occurrence rate of field failures^{6,28}. Here, we use the term “manufacturing performance” to broadly describe these performance metrics. Given the thin profit margins (often 2–3%)⁸⁶ with which battery factories operate, quality concerns are often in tension with these manufacturing performance indicators. For instance, the decision of what to do with a batch of cells with marginal failures might be heavily debated between production and quality teams. Furthermore, an engineering team may require a couple of weeks to assess the risk of a potential quality issue, but a production team must often make decisions on daily or even hourly timescales to avoid inventory buildup or, worse, a line shutdown. However, allowing defective cells to escape the factory carries significant reputational risk for both the cell producer and OEM and may require substantial engineering resources to resolve in the future.

One underappreciated attribute of manufacturing performance is dynamicism, or the ability to respond to change. In an overly idealized view, a battery factory statically maintains fixed operational objectives. In reality, a factory must dynamically respond to a variety of internal (e.g., new equipment, new process learnings, new cell designs, business objectives) and external (e.g., improved or less expensive materials and components, new learnings from the field, market demand, policy incentives) factors. While too many simultaneous demands can threaten production stability, dynamicism is a key ingredient of manufacturing success.

Finally, we mention that the sustainability of battery production is becoming an increasingly important manufacturing performance metric. For instance, an estimated 30–65 kWh are consumed in the factory for every kWh of cells produced^{45,87}. Furthermore, scrap rates can range from <5% to as high as 90% during ramp-up^{28,88,89}; while recycling these scrap materials can improve the sustainability of battery production, better yet is to reduce the rate of scrap in the first place. Generally speaking, a strong emphasis on quality and quality control can be a powerful lever to minimize wasted material and energy during battery production.

Managing battery quality in production

Given the frequency, severity, and inevitability of battery quality issues, both battery producers and manufacturers of battery-containing products must manage battery quality. Quality control often involves difficult choices made under high uncertainty, but these decisions must be made to avoid the potentially devastating risks of inaction.

In Fig. 5, we propose four pathways for managing battery quality in production. These approaches are derived from process capability analysis, which is commonly employed in manufacturing environments⁹⁰. While each of these pathways is individually presented and discussed, an “all-of-the-above” approach is often required in practice. Throughout this section, we use the example of electrode overhangs (subsequently referred to as simply “overhang”) as a

canonical example of a battery quality issue. Insufficient overhang may cause lithium plating, which may cause an internal short and, in extreme cases, thermal runaway^{52,74,75}.

A typical requirement has a design target, such as 550 μm for overhang. Each design target has specification limits, or “spec limits”, which define the acceptable tolerance range for a given requirement. These spec limits might include a lower spec limit (LSL), upper spec limit (USL), or both. For instance, the LSL and USL for overhang might be 300 μm and 1000 μm (Fig. 5a). The motivations for the LSL and USL may differ: in the case of overhang, the LSL would likely be set by reliability or safety concerns (i.e., lithium plating), while the USL might be set by performance or cost concerns (i.e., insufficient positive electrode material and thus low energy, or the cost of excess negative electrode material). The overhang population in production may differ from the design target (e.g., an overhang population with a mean of 500 μm and a standard deviation of 75 μm). A process in violation of its spec limits would be considered a process control failure.

Pathway 1: Expand specification limits

In some ways, the simplest approach for a cell producer to take toward a quality issue is to expand the spec limits (Fig. 5b). With this approach, no changes are required to the manufacturing process. In some cases, this approach is perfectly valid; for instance, the LSL for overhang could be decreased from, say, 300 μm to 200 μm if the cells were destined for operation in a lower-rate, lower-voltage, and/or lower-lifetime application than their original target use case. However, in many cases, the specifications cannot be changed due to clear safety concerns or even contractual obligations from the cell supplier to its downstream stakeholders.

In other cases, widening specification limits—that is, producing cells that are less reliable and/or safe—can be implemented with coordination from downstream stakeholders. These stakeholders could include module/pack design teams as well as actual end users. For instance, EV modules and packs are generally designed with some reliability and safety countermeasures in mind^{18,19}. A typical pack is passively balanced, which often implies poor resiliency against extreme open-circuit and short-circuit failures^{18,19}. In fact, packs with passive balancing are often limited by the weakest cell in a module/pack, where a cell is considered “weak” with regards to its initial energy, remaining energy, or short-circuit current^{15,22,23}. Active balancing approaches are employed in some settings, but they add significant cost, weight, and complexity to the pack relative to passive balancing¹⁶. Additionally, packs are often “over-designed” for safety in that many packs include “extra” thermal insulating materials to prevent a thermal runaway from propagating to adjacent cells, adding additional cost and mass to the pack^{18,19}. While this additional safety margin certainly has benefits, improving cell-level safety could ease requirements for module- and pack-level design, in turn enabling decreased costs and improved performance (i.e., range). Finally, coordinating these changes can be difficult especially if the cell production team and the module/pack design team are from different businesses or organizations and thus have misaligned objectives and/or incentives.

The second type of stakeholder that can be impacted by upstream specification changes is the end user. Specifically, if the cell spec limits are expanded in response to challenges meeting the spec in production, the cell operating limits can be tightened to maintain iso-reliability and -safety for the end user. For instance, if a cell production team is concerned about overhang spec violations, the upper cutoff voltage (which impacts vehicle range) or maximum charge rate of the product could be decreased to maintain similar levels of reliability and safety in operation^{33,47,52}. One advantage of this approach is that in extreme cases, the operating limits can be dynamically modified in the field if remote firmware control capabilities are present⁹¹; however, clear communication with the customer regarding any changes is

essential. Of course, the primary downside of this approach is reduced customer utility. In the example above, decreasing the range and/or fast charging time is a highly visible change and will certainly be an unpopular decision among design teams, marketing teams, and customers alike.

Carefully setting specifications is challenging. For instance, the lower specification limit for overhang should certainly be greater than zero, but by how much? The answer depends on not only cell design factors (e.g., electrode thicknesses), production factors (e.g., process capability), and operational factors (e.g., product use case) but also business factors (e.g., financial impacts of yield and throughput metrics, reputational tolerance for quality issues, customer service costs, and more). Furthermore, the timescales of lithium nucleation in the overhang region, lithium nuclei turning into a dendrite, and a dendrite causing a noticeable internal short are worth considering in setting the spec limits but can be difficult to estimate. However, for requirements with potential safety implications, caution is prudent when setting and changing these requirements.

Pathway 2: Shift the population mean

A second pathway for managing quality is shifting the population mean—in other words, changing the cell design to be more resilient to failure (Fig. 5c). For example, if a production team were struggling with a wide distribution of overhang, resulting in LSL overhang violations, the design and production teams could agree to increase the overhang design target and the USL by reducing the length of the positive electrode and thus increasing the mean overhang length. However, since the cell now contains less lithium inventory, this change would lead to lower energy density as well as higher cost per unit of energy; designing for high quality and reliability often must come at the expense of performance. Another example of this tradeoff is the use of protective components, such as current interrupt devices, which improve cell safety but add cost and mass⁷². More broadly, new cell chemistries with purported safety advantages, such as solid-state batteries, may be even more sensitive to these types of tradeoffs during production due to their increased cell energy and thus increased safety risk⁹². In short, performance and cost are almost always in tension with quality and reliability, and this balancing act is often enormously difficult in light of extreme market pressure to both improve battery performance and reduce cost.

Pathway 3: Tighten distribution

A third pathway is tightening the distribution of a process parameter, or improving process capability and thus product conformance (Fig. 5d). In principle, this approach has a few downsides: the downstream customers receive a more uniform product and higher quality without any compromises to performance. In fact, improved conformance can be leveraged for increased performance. In Supplementary Fig. 2, we illustrate how increased overhang conformance could translate to a design change that increases cell energy (and thus decreases cost per unit energy as well).

In some cases, cell producers may be able to find low-hanging fruit to improve overall process capability. In practice, however, these types of improvements are often limited by both cost and time. Improving conformance/reducing variability can be an expensive exercise; in the case of overhang, a process engineering team might decide to recalibrate the coating, winding, and/or stacking equipment more frequently, leading to increased operating costs and decreased throughput. Furthermore, for more interdependent failure modes, an understanding of which of the hundreds or even thousands of process parameters may have the biggest impacts on variability is often lacking; even worse, in a process as complex as battery production, changing one parameter will inevitably have downstream effects on another process step or failure mode. Finally, a production team will generally have little interest in tweaking the parameters of an

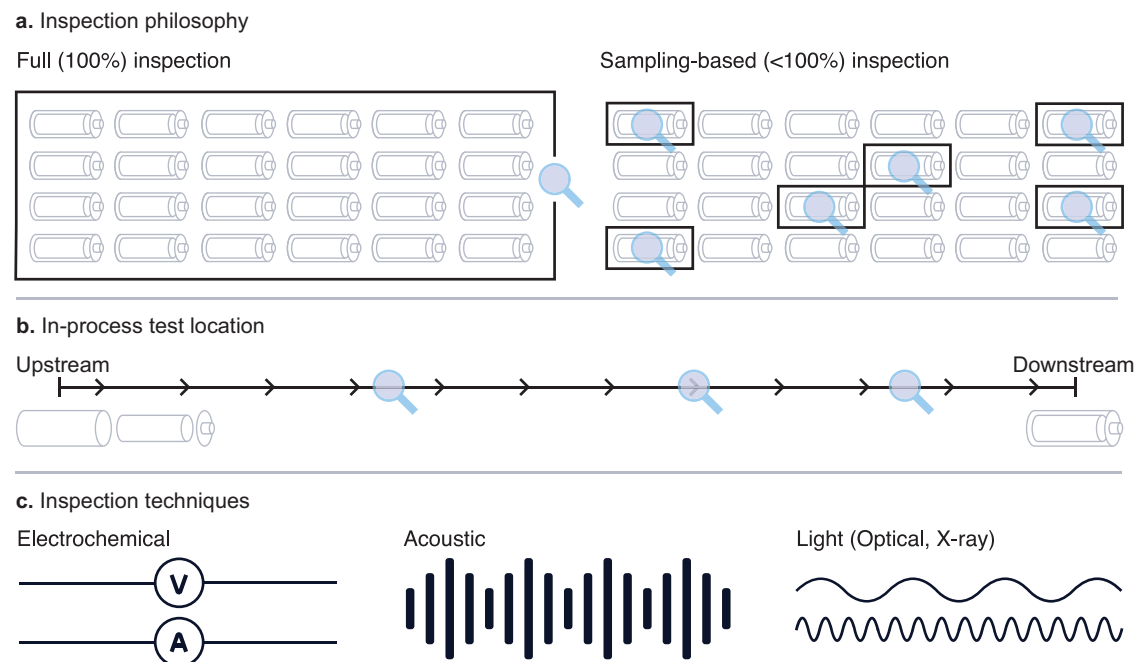


Fig. 6 | Key considerations for designing a strategy for battery quality inspection. **a** Inspection philosophy: either full inspection (100% sampling rate) or sampling-based inspection (<100% sampling rate). **b** In-process test location: either

upstream, downstream, or in between. **c** Inspection techniques: either electrochemical, acoustic, or electromagnetic (e.g., visible light or X-rays). Various inspection techniques are further discussed and illustrated in Table 1 and Fig. 7.

otherwise successful process for an uncertain benefit. In short, reducing variability may be appropriate in some cases but is often impractical in practice. Generally speaking, this approach is counter to design-for-manufacturability principles in which processes should not require narrow process windows to succeed⁹³.

Pathway 4: Improve inspection

The last pathway we examine is improving quality inspection and defect detection during production (Fig. 5e). As we will discuss, improved inspection may or may not directly change the defect rate depending on the specifics of the approach. While inspection does not fix the root problems on its own, a comprehensive inspection strategy might provide enough relief to prevent some of the most painful tradeoffs from being made. We recommend McGovern et al.²⁵ as an excellent review of this topic for a deeper understanding.

We believe that designing an inspection strategy for battery production involves at least three key considerations (Fig. 6). Per usual, an “all-of-the-above”, case-by-case basis approach is warranted.

The first consideration is inspection philosophy (Fig. 6a). At a high level, two inspection philosophies are full inspection (100% sampling rate) and sampling-based inspection (<100% sampling rate). In full inspection, an inspection test is used as an in-process pass/fail check. Assuming the test is accurate, full inspection obviously prevents defective cells from continuing downstream. Full inspection is often suitable for inexpensive diagnostics where inspecting all or most cells is achievable, such as in-line vision²⁵, but this approach may add too much operating cost for expensive tests. In contrast, the philosophy of sampling-based inspection is to use the insights from inspection tests to root cause issues and estimate the escape rate of defective cells. Sampling-based inspection strategies have been studied and tested for nearly a century and can be quite sophisticated^{94,95}. A core assumption of sampling-based inspection is that cell production issues can be traced to one or a couple of suspect process steps or equipment, which is often but not always the case⁹⁶. As a result, careful sampling, monitoring, and analysis can be used to pinpoint many cell failure issues.

This approach is often suitable for more expensive diagnostics where 100% detection would add an unacceptably high operating expense. For sampling-based detection, rapid analysis, feedback, and response are essential to ensure that the insights prevent a small issue from intensifying. In other words, the quality team must remain vigilant to prevent a defective process from remaining defective for days (as opposed to being resolved in hours).

A second consideration for designing an inspection approach is in-process test location (Fig. 6b)^{97,98}. Battery production involves many steps, each of which can introduce new issues. Location optimization must balance the relative advantages of upstream and downstream locations. An upstream test minimizes wasted material and wasted time, as problems can be root-caused closer to their source. In contrast, a downstream test maximizes defect detectability because the cell is closer to its final state; for instance, some defects may become readily detectable after the battery formation manufacturing step. Furthermore, cell inspection may continue after the cell has left the production facility. For instance, in addition to the outgoing quality control (OQC) inspection performed by the cell producer, an EV producer may perform incoming quality control (IQC) for incoming cells as the EV producer bears significant reputational risk with a safety incident. We note that in the semiconductor industry, an ensemble of test methods is performed after each process step since every process step can cause an issue. Ultimately, the value of each inspection step must be balanced by its cost.

A final consideration is the inspection tests themselves (Fig. 6c). Of course, one of the most important attributes of a test is its ability to detect the defects and features of interest. By extension, the test method must be suitable for its location in the production process. Component tests may be more appropriate for inspecting upstream steps, such as electrode coating; however, testing the nearly complete product at the end of production may require more advanced characterization techniques for full-cell inspection. We summarize key attributes of battery quality inspection techniques in Table 1; specifically, ideal battery quality inspection techniques should be

Table 1 | Key requirements of cell-level battery quality inspection techniques

Technique	Nondestructive	Scalable to ≤ 10 s/cell	Full-cell inspection	Spatially resolved	Resolution of ≤ 50 μm
Cycling and storage	No	No	Yes	No	N/A
Ultra High Precision Coulometry (UHPC)	No	No	Yes	No	N/A
Formation checks (e.g., OCV decay)	Yes	No	Yes	No	N/A
Electrochemical Impedance Spectroscopy (EIS)	Yes	Yes	Yes	No	N/A
High Potential testing (HiPot)	Yes	Yes	Yes	No	N/A
Dissection	No	No	Yes	Yes	Yes
Cross-section	No	No	No	Yes	Yes
In-line vision	Yes	Yes	No	Yes	Yes
Acoustic imaging	Yes	Yes	Yes	Yes	No
2D X-ray imaging	Yes	Yes	No	Yes	Yes
3D X-ray imaging (CT)	Yes	Yes	Yes	Yes	Yes

Materials-level characterization techniques, such as electron microscopy, are excluded from this table. A test duration of ≤ 10 s is important so that a meaningful number of cells ($\geq 10\text{k/day}$) can be sampled from production. Spatial resolution on the order of $10\text{--}100$ μm is important for detecting many critical battery defects, such as electrode overhang violations^{52,74,76} and metallic particle contaminants^{26,27,78}. All of these techniques are suitable for all major cell form factors (i.e., cylindrical, pouch, and prismatic), although geometrically larger cells are generally more difficult to image than smaller cells. In our opinion, an ensemble of complementary inspection techniques is the best defense against battery quality issues.

nondestructive, fast, inclusive of the full cell, and spatially resolved with high resolution.

Perhaps the most standard defect detection test performed in battery manufacturing today is measuring the leakage current during rest after formation^{85,99,100}. This test can directly capture a key product requirement: no internal shorting. Additionally, the marginal cost of this test is often seen as acceptable since cells have already been placed in electrical fixtures for the formation process. However, this approach has a number of shortfalls intrinsic to any electrochemical test. First, while this test can detect shorts present at the time of the test, it cannot detect latent defects (i.e., defects that will activate sometime after the test, likely in the field). Second, electrochemical tests measure the global (i.e., non-spatially resolved) state of the cell, which provides limited diagnostic insight into the root cause of failure. Finally, this test can be very slow (\sim weeks) to compensate for variability in temperature, contact resistances, the cells themselves, and more—leading to large capital and operational expenses at the factory. In our opinion, measuring post-formation open-circuit voltage is necessary but insufficient for quality inspection during battery production.

Many other techniques are employed for battery quality inspection, such as cycle life and storage life testing^{45–47,50}, coulometry^{101,102}, electrochemical impedance spectroscopy (EIS)⁵⁶, electronic checks (e.g., high-potential testing, or HiPot)^{103,104}, dissection^{57,60,71,105}, cross-section^{57,106}, vision²⁵, acoustic imaging^{107,108}, and X-ray imaging^{25,41,105,109–111}. We briefly discuss these techniques here, although we again refer interested readers to McGovern et al.²⁵ for a deeper understanding of the nondestructive techniques. As discussed, while electrochemical techniques (lifetime, coulometry, OCV decay during formation, EIS, and HiPot) are commonplace, they are not spatially resolved and thus cannot identify latent defects and provide limited diagnostic ability. Lifetime and coulometry testing require weeks to months of testing time and are destructive in that they reduce cell energy and thus cause the cell to no longer meet its specifications. Dissection, in which a cell is torn open and the components are examined via photography or electron microscopy^{57,60,71,105}, and cross-section, in which a cell is set in epoxy and then cut open to reveal the internal structure via photography or electron microscopy^{57,106}, are both highly informative but destructive and labor-intensive. Lastly, optical imaging (vision) is widely employed throughout the battery manufacturing process²⁵, but end-of-line vision can only identify surface-level cell quality issues (e.g., can or terminal corrosion, significant crimping issues, etc.). In short, while all of these standard techniques provide value, few can nondestructively evaluate the cell's

internal structure with spatial resolution—the critical attribute for latent defect detection.

In Fig. 7, we compare the three nondestructive full-cell imaging techniques — ultrasound (Fig. 7a), 2D X-ray (Fig. 7b), and 3D X-ray (Fig. 7c) on the same “4680” (46 mm diameter, 80 mm height) cylindrical cell (BYD FC4680). The experimental details are discussed in Supplementary Discussion 2. Figure 7a displays the root-mean-square (RMS) value of the amplitude of the ultrasonic measurement; higher values tend to indicate higher electrolyte saturation. Thus, Fig. 7a suggests that this cell has poorer electrolyte saturation at a Z position of around 50 mm than at other Z positions. Figure 7b displays three different 2D X-ray images of the same cell: a full-cell image, an image centered at the top overhang region, and an image centered at the bottom overhang region. The overhang region is visible and appears uniform, although interpreting the overhangs is challenging as all material in the X-ray path is convoluted together. Finally, Fig. 7c displays selected slices from 3D X-ray inspection (computed tomography, or CT). The individual electrode layers, overhangs, cell structural features such as tabs, and even the electrolyte meniscus in the core of the cell can be clearly resolved. The cell appears to be of high quality; the overhangs are relatively uniform and of sufficient length, and none of the quality issues displayed in Fig. 4 are observed. In our view (although please see our statement on competing interests), CT imaging provides exceptionally rich insights into battery quality^{61,105,109,110} with a clear pathway for high scalability^{111–114}. Ultimately, however, we believe an arsenal of characterization techniques is the best defense against battery quality issues in production.

Of course, these inspection techniques add cost, which reduces the already-thin profit margins of battery manufacturing. The cost of these techniques depends on many technical (e.g., sampling rate, cell size, equipment specifications, measurement time, data management specifications) and business (e.g., cost of capital, cost of labor, negotiating power of the sourcing team) factors. These costs can be calculated on either a per-cell or per-Wh basis. Some techniques, such as dissection and cross-section, typically have low capital costs but high operational costs, while other techniques, such as 2D X-ray imaging, typically have high capital costs but low operational costs. Ultimately, of course, the return on investment determines if an inspection technique should be included in production. In Supplementary Discussion 3, we estimate that the cost for 2D X-ray is \$0.05/kWh, while the cost of 2.5% pack field failure during the pack warranty period is \$7.50/kWh. Overall, in our experience, the massive costs of slow factory ramp times, low yield and/or throughput, and field failures due to safety/

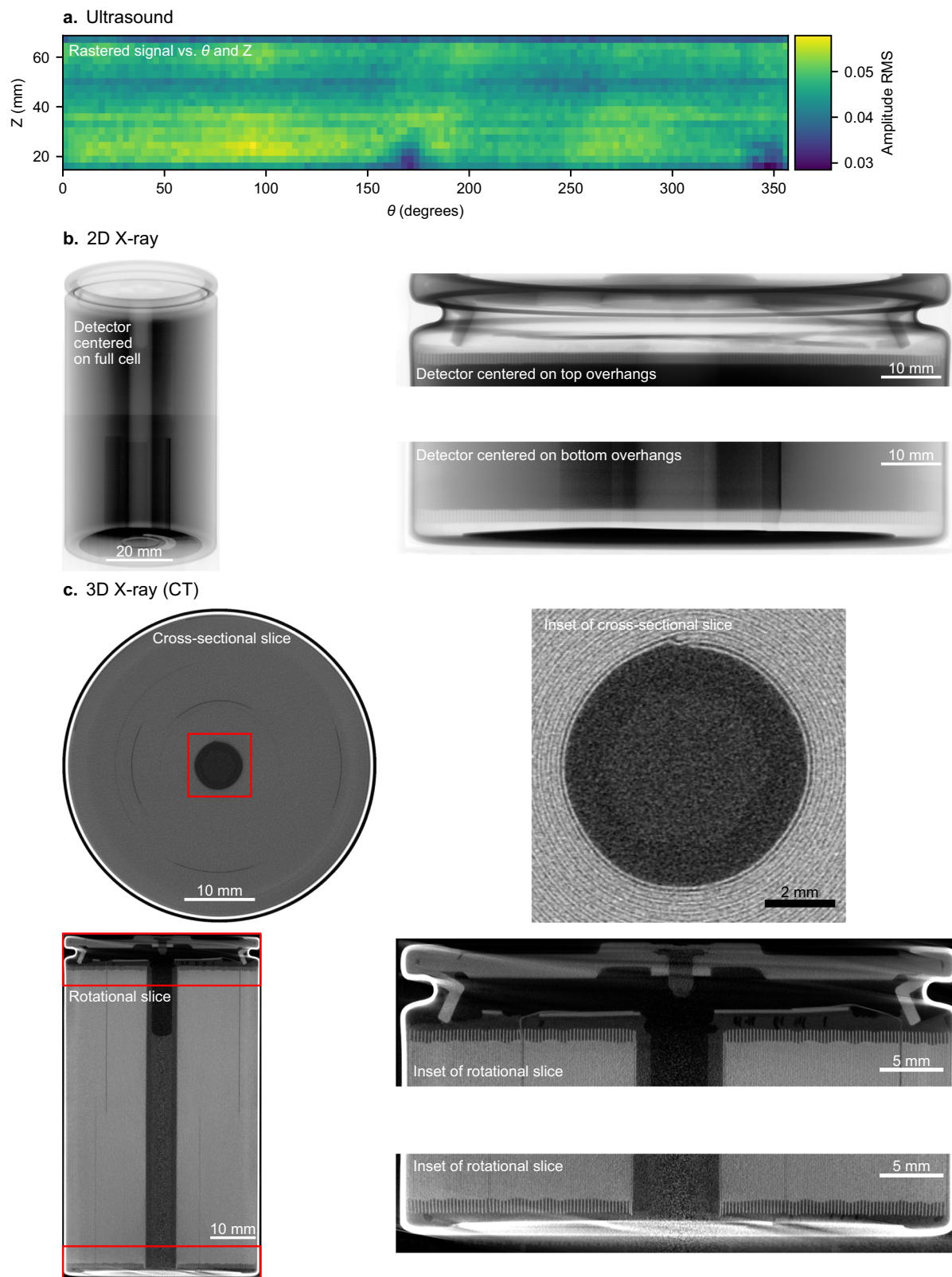


Fig. 7 | Comparison of nondestructive, full-cell, spatially resolved techniques for evaluating battery quality. All measurements were obtained on a BYD FC4680 cylindrical cell. Experimental details are provided in Supplementary Discussion 2. **a** Ultrasound (acoustic) imaging. The root-mean-square (RMS) value of the amplitude is displayed as a function of Z (position along the cell height) and θ . The acquisition time was three hours, although this time could be reduced with a multi-

transducer pair system as opposed to the single transducer pair system used here. **b** 2D X-ray imaging. Three distinct images are presented: an image of the full cell, an image centered on the top overhang region, and an image centered on the bottom overhang region. The acquisition time for each image was 125 milliseconds. **c** 3D X-ray imaging (computed tomography). Two different slice orientations, along with insets of key regions, are displayed. The acquisition time was 73 s.

reliability issues typically support investment in a comprehensive inspection strategy.

Inspection tests during production can generate massive quantities of data^{115,116}. These data can serve as a continuously updated snapshot into battery quality if carefully organized and managed—and especially if combined with data from the manufacturing process. As previously discussed, dynamicism is a key ingredient to manufacturing success; the data from inspection tests enable process resiliency in that engineering, production, and quality teams can quickly understand the impact of a process change on cell quality. In particular, these records are invaluable in case of a field failure event to evaluate the size of the affected cell population years after the cells were produced. Data analytics and artificial intelligence tools for anomaly detection and correlation analysis could be powerful aids to glean insights from this data^{115,116}.

Lastly, we discuss the dependence of quality and defect detectability on form factors. The battery industry is currently pursuing three primary form factors: cylindrical, pouch, and prismatic. While many design criteria influence the optimum form factor for a given application, we propose that both quality and “quality inspectability” are also important. Currently, the industry lacks a clear view of the relationship between form factor, quality, and quality inspectability. Major considerations for quality include wound vs. stacked jellyrolls, the strength of the casing (with pouch cells having the least rigid case), and intrinsic heterogeneities from intra-cell thermal, mechanical, and (electro)chemical gradients^{59,117–120}. Major considerations for detectability are overall size and aspect ratios (i.e., is a cell geometry “2D”, such as a pouch cell, or “3D”, such as a cylindrical cell). Lastly, for EVs, the number (and arrangement) of cells in a pack is an important factor for pack reliability (see Fig. 3)^{14,17}. Form factors that generally house higher-energy cells, like prismatic, typically have hundreds of cells per pack; form factors with smaller cells, like cylindrical, typically have thousands of cells per pack²⁴. In this case, the optimum form factor from a quality standpoint depends on whether the most concerning defects occur primarily per unit of energy or per cell. Different defects will have different dependencies. For instance, electrode-level defects will likely occur per unit of energy, and thus more cells will fail for higher-energy form factors; conversely, cell-level defects like weld issues will likely see higher failure rates for lower-energy form factors.

Conclusions

The need for planetary-scale battery production has never been clearer, and cell suppliers around the globe are racing to ramp capacity. However, ensuring high quality during battery production is an immensely challenging endeavor with enormous financial, reputational, environmental, and human stakes. Yet the battery quality challenge is underappreciated given its criticality to global electrification efforts. We believe this problem is of similar importance to improving battery performance, the predominant focus of academic and industrial battery engineering today; in fact, in many ways, performance and quality are closely intertwined and often come into conflict. Both cell producers and OEMs must properly weigh both factors in cell design and selection.

The industry has a long road ahead to enable successful management of battery quality. We believe the following steps would be immensely beneficial for the industry. First, a complete standardized taxonomy of battery failure modes would enable a common language and understanding of battery quality issues. Similarly, a library of tests for each failure mode would enable rapid qualification and issue resolution throughout the industry. While some standard tests exist today¹²¹, a much larger test library is needed to match the wide variety of failure modes and requirements. Additionally, modeling tools to answer critical quality questions (e.g., how to set the spec limits for overhang) will be highly beneficial for the industry. Furthermore, faster, less expensive, and more information-rich battery quality characterization techniques are sorely needed to quickly test the massive quantities of cells

produced daily at a typical cell production facility—along with user-centric analytics tools to turn this massive volume of data into actionable insights. Lastly, stronger efforts around preventing counterfeit and low-quality cells, as well as developing stronger quality and safety certifications, will strengthen the reputation of battery-employing products. Overall, we believe that a collaborative industry-wide effort to improve battery quality would bolster investor, legislative, regulatory, and customer confidence in this technology; conversely, every publicly reported safety event threatens the success of the entire industry.

Battery quality also has important impacts on questions around battery reuse and recycling¹²². While energy retention is an important metric to determine suitability for reuse, the presence of cell failure and defects arguably should be the primary gating item for this decision. Cost-effective characterization techniques for battery quality may enable more cells to be reused in a second-life application instead of immediately recycled⁷⁸.

While regulatory efforts around battery safety are only just beginning¹³, we expect more will arise as more battery safety incidents occur. Existing proposals such as the EU’s “battery passport” include a quality component^{123,124}. In our opinion, new regulations should not impede creativity and progress in this critical and burgeoning industry, but they should provide sensible safeguards to protect public safety. In particular, preventing low-cost, poor-quality cells from entering the market would help avert the worst of these safety issues from occurring^{10,71}.

We hope our perspective provides a small step toward a safely electrified future.

Data availability

All data used to generate the figures is available at <https://github.com/petermattia/battery-quality-at-scale>.

Code availability

All code used to generate the figures is available at <https://github.com/petermattia/battery-quality-at-scale>.

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Author contributions

Peter Attia: Conceptualization, Writing - Original Draft, Writing - Review & Editing, Visualization. Eric Moch: Writing - Review & Editing. Patrick Herring: Writing - Review & Editing.

Competing interests

The authors declare the following competing interests: P.M.A., E.M., and P.K.H. are co-founders with employment and financial interests in Glimpse Engineering Inc., which specializes in high-throughput CT scanning for batteries.

Additional information

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