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Control decides who survives in battery manufacturing

Scale, variability, and the stability threshold of gigafactory production

Industry perspective | Dirk Schneider

comet
x-ray



Content

Introduction	4
The structural cost of invisible uncertainty	6
Capacity vs. productive capacity	7
Technology readiness vs. integration complexity	9
Europe vs Asia - governance, scar tissue, and tolerance for pain	10
Inspection as constraint, not enabler	12
What X-ray solves – and what it does not	13
Comet between industries - strengths, gaps, and responsibilities	14
Conclusion	15

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As Market Segment Manager at Comet X-ray, Dirk drives growth in battery quality control by translating customer requirements into scalable, high-performance solutions that meet real-world challenges in battery manufacturing.

He brings over 10 years of experience at the Comet Group across product and market segment management. As Product Manager for microfocus X-ray sources, he strengthened product strategy and accelerated development by aligning technology more closely with industrial needs.

Prior to Comet X-ray, Dirk was Technical Product Manager at ebeam Technologies, where he developed advanced solutions for surface sterilization and material enhancement. He began his career in R&D roles at DuPont and Chemours, contributing to applied research and industry collaboration.

Dirk holds an Executive MBA from IMD Lausanne and a PhD in Chemistry from Johannes Gutenberg University Mainz.

He combines technical depth with a clear commercial focus, helping customers improve quality, reduce risk, and increase performance in demanding applications such as battery manufacturing.

Introduction

Scale is visible. control is not.
Battery manufacturing today is often discussed in terms of scale. Gigafactories are announced, capacity targets are published, and investment volumes are tracked closely. These indicators are easy to measure. Control is not.

Yet control ultimately determines whether scale creates economic value. Without stable processes, expanded output does not translate into predictable yield, protected margins, or reduced risk. Instead, hidden variability accumulates in the background.

Ramp-up is commonly described as a temporary phase in which processes stabilize and performance improves. Many facilities remain in extended ramp-up conditions far longer than expected. The symptoms are rarely dramatic. Yield plateaus persist. Scrap increases gradually. Root causes remain only partially understood.

The economics of small deviations
At pilot scale, variability often appears manageable. A defect rate of 0.5% may seem insignificant when producing 10.000 cells per year. At a gigafactory scale, the same rate can translate into one million defective cells annually. With an assumed loss of 25 USD per unit, this represents roughly 25 million USD in direct economic impact.

As production volume increases, the cost of defects escalates through scrap, corrective actions, warranty exposure, and reputational risk. The economic effect of variability is therefore magnified by scale. Translating high-throughput processes into consistently stable yield becomes a structural challenge rather than a technical detail.

Industry progress is still largely measured by capacity installed and capital deployed. These metrics describe ambition but reveal little about operational stability. Process fragility often becomes visible only after scale has already been achieved.

Battery manufacturing rarely fails to the point of complete production stoppage. More often, failure emerges gradually. Small uncertainties in coating uniformity, material purity, alignment, or welding precision propagate along the line. Minor deviations accumulate into systemic instability.

From expansion to execution
During the early growth phase of the battery industry, priorities were largely external. Companies focused on securing funding, building capacity, and establishing supply chains. Success was defined by how quickly new lines could be brought online.

Today, competitive pressure has shifted inward. Stabilizing yield, controlling defect propagation, ensuring safety at volume, and maintaining customer trust have become decisive capabilities. Operational execution is replacing expansion speed as the key differentiator.

Inspection technologies based on non-destructive testing are increasingly treated as essential process tools. However, their integration introduces technical, financial, and organizational friction.

Inspection increases costs, complicates system architecture, and exposes variability that organizations may prefer not to confront. As a result, many manufacturers delay investment until instability becomes economically visible.

Control as a structural advantage
In a consolidating industry, competitive durability will depend on the ability to make variability measurable and manageable. Facilities that integrate inspection early, align engineering and quality functions, and connect inspection data directly to process adjustment are more likely to achieve stable output.

Inspection then shifts from a reactive quality measure to an operational control layer. It does not eliminate uncertainty. It defines its boundaries.

Control is indeed at the center of the solutions, but an unattractive task

Scale is visible. Control is not.

The structural cost of invisible uncertainty

Variability lives everywhere
Process variability does not occur at a single step in battery manufacturing. It runs through the entire production chain, from electrode coating and calendaring to stacking, welding, and electrolyte filling.

Certain defect zones carry a particularly high risk. In electrode production, these include agglomerates, pinholes, contamination, and uneven coating loads. During cell assembly, common issues include anode-overhang deviations, foreign-particle inclusions, misalignment, and imperfect welds.

At pilot scale, many of these defects appear statistically negligible. At a gigafactory scale, they become economically unavoidable.

The limits of sampling
Statistical sampling and destructive testing can identify trends, but they struggle to detect low-frequency, high-impact anomalies. These rare defects often remain invisible until they propagate across large production volumes.

Manufacturers, therefore, adopt practical containment strategies. Increasing sampling frequency at critical steps can improve visibility. Fast inline optical inspection can be used to pre-screen suspect areas before slower CT inspection provides deeper analysis.

These approaches reduce risk, but only if implemented early enough. When detection is delayed, defective cells may already have reached OEM validation or entered field deployment. At that point, the consequences are no longer technical. They are financial, contractual, and reputational.

Instability rarely looks dramatic
This dynamic is structural rather than exceptional. Yield erosion of just a few percentage points at the GWh-scale can materially compress margins in capital-intensive operations. Integrating inspection reactively under production pressure is significantly more disruptive and more expensive than designing it into the system architecture from the beginning.

Battery manufacturing doesn't fail because ambition is missing. It fails because uncontrolled uncertainties multiply at scale. Failure is therefore less likely to appear as a sudden shutdown. More often, it takes the form of prolonged operational fragility.

Four signals of hidden instability
For production leaders, this fragility typically manifests in three measurable ways:

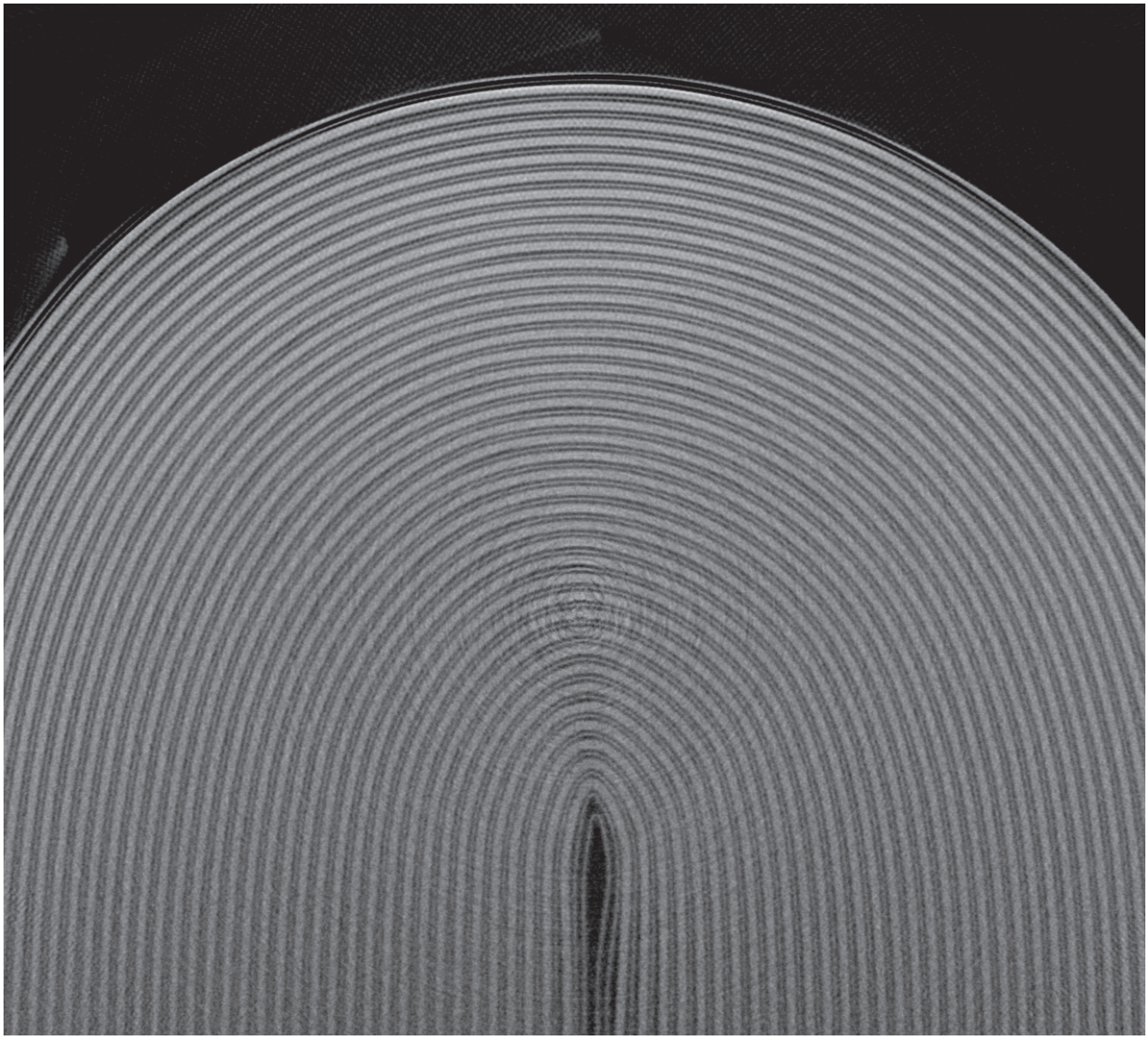
- **Yield compression**
  Scrap rates increase during ramp-up and stabilize above target levels. For example, scrap may remain at 8% of throughput after six months, instead of the planned 4%.

- **Ramp elongation**
  Qualification timelines extend. Instead of achieving a stable yield within six months, full-process qualification may take 9 to 12 months or longer.

- **Capital inefficiency**
  Installed lines operate below nameplate capacity. Productive output may reach only 80–85% of expectations over sustained periods, reducing returns on invested capital.

These effects are rarely emphasized publicly, yet they shape competitive durability. Facilities that cannot stabilize output risk losing contracts to manufacturers demonstrating more predictable yield and stronger quality performance.

Visibility before optimization
Advanced quality systems, intelligent equipment, and traceability can support yield improvement. But optimization presupposes visibility. Without integrated control, factories risk stabilizing noise rather than processes. The cost of invisible uncertainty is not limited to scrap. It delays learning. At an industrial scale, delayed learning becomes expensive.



Capacity vs. productive capacity

Over the past few years, global battery manufacturing capacity has expanded rapidly. New factories have been announced, installed capacity has increased, and assembly speeds have improved. In practice, however, installed capacity and productive capacity often diverge.

Gigafactory ramp-up is therefore less a scaling exercise than a stabilization challenge. Building a robust production system is a key differentiator for a battery factory's effectiveness and economic value.

Economic value does not come from theoretical maximum output. It comes from stable first-pass yield and predictable throughput. Many ramp-up failures can be traced back to basic process constraints that were underestimated or addressed too late. At an industrial scale, three structural dynamics explain why productive capacity remains difficult to achieve.

Interaction complexity
Technologies that perform reliably in isolation can behave unpredictably once integrated into a contin-

uous production line. Material variability, equipment drift, and human workarounds interact in ways that are difficult to foresee.

Small local deviations can propagate downstream. In one facility, a minor variation in coating thickness led to inconsistent electrode edges. This triggered misfeeds and alignment errors during welding, eventually forcing a temporary shutdown until the root cause was identified. Similar dynamics appear in deviations in anode overhang, tab positioning, weld quality, electrolyte absorption, and mechanical deformation. Individually, these effects may be manageable. Combined, they create systemic instability.

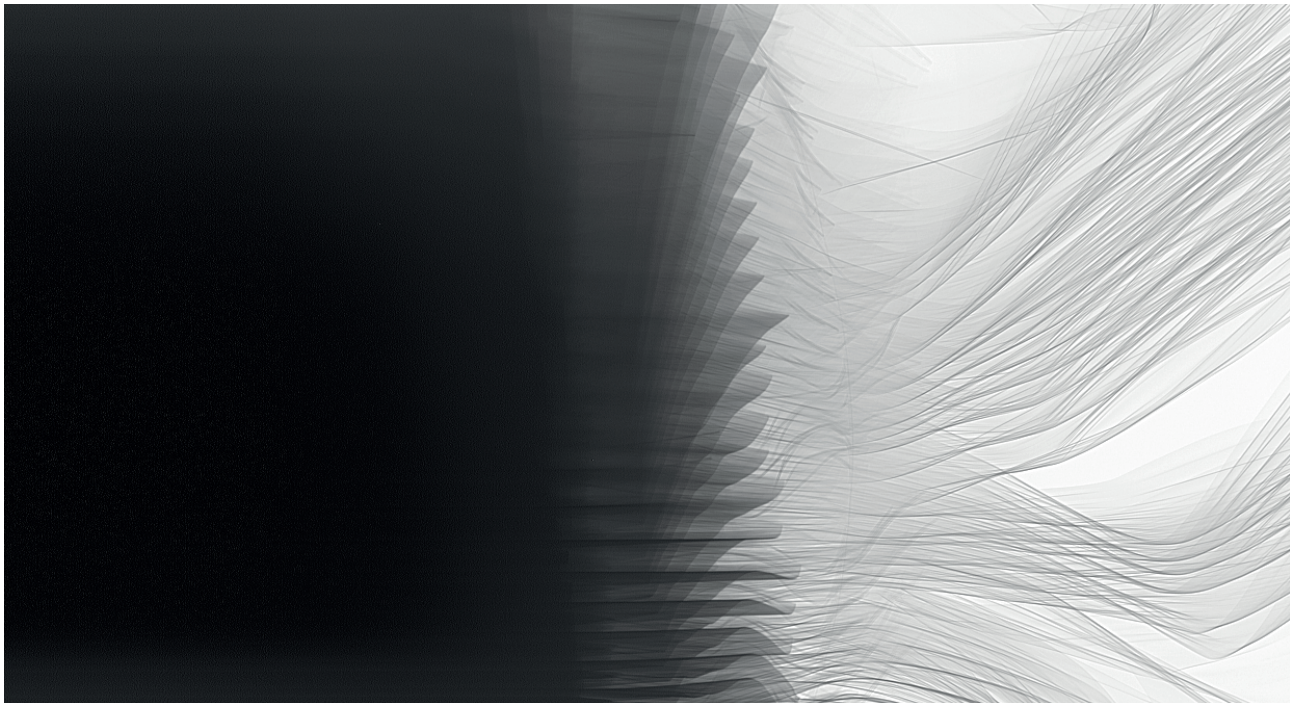
Feedback latency
Production stability depends not only on detecting defects, but on detecting them quickly enough to influence ongoing output. Destructive sampling provides statistical confidence but limited immediacy. Offline non-destructive analysis offers deeper insight but slows feedback cycles. CT inspection, while powerful, still faces throughput constraints that limit real-time deployment in many contexts.

This creates a structural tension: inspection depth and inspection speed compete. When feedback cycles operate more slowly than production cycles, variability accumulates before corrective action can take effect.

Margin Sensitivity
Gigafactories operate under narrow economic margins. Even small yield deviations can determine whether a facility achieves profitability. Premature scaling on unstable processes as a "breakneck issue" for the economic viability of many battery-related scale-ups. When production volume increases before process control is secured, scrap compounds, rework intensifies, and financial tolerance declines.

Failure rarely appears as an immediate shutdown. More often, facilities enter prolonged operational fragility, operating below expectations while capital remains tied up.

Installed capacity is an engineering metric. Productive capacity is an operational achievement.



Technology readiness vs. integration complexity

Battery manufacturing technologies have advanced rapidly. Improvements in cell chemistry, process modelling, and the use of artificial intelligence for performance prediction have created the impression that core challenges are largely solved.

At laboratory and pilot scale, coating, winding, welding, and cell formats are well understood. Simulation accuracy continues to improve. Yet the decisive challenge is not whether individual processes work in isolation. It is whether they remain stable once integrated into high-throughput industrial production. Superior chemistry has little value if it cannot be reliably transferred to manufacturing.

Technological readiness, therefore, does not automatically translate into controllable manufacturability. Three structural dynamics explain why.

Coupled variability
Processes validated independently often behave differently when combined in continuous production.

Coating variability influences drying and calendaring performance. Welding quality affects resistance and safety margins. Electrolyte distribution depends on stacking precision and density uniformity. Individually manageable deviations interact at industrial speeds and volumes.

What appears stable at pilot scale can become unstable when multiple sources of variability converge.

Learning constraints
Industrial scaling assumes predictable learning curves in which yield improves and scrap declines. In practice, learning depends on how quickly and accurately defects become visible.

Traceability systems and intelligent quality tools help shorten feedback cycles. When visibility is delayed or incomplete, ramp-up extends, and margins erode. Production teams may optimize based on partial information, stabilizing symptoms rather than root causes.

From lab-ready to line-ready
Technology readiness is often defined by the success of pilot tests. Industrial readiness requires something different: robustness under automation, material variability, and sustained throughput.

At pilot scale:
- Expert operators intervene frequently
- Feedback is immediate
- Process variability is contained and observable

At an industrial scale:
- Automation limits manual correction
- Feedback is often delayed or sampled
- Variability can propagate silently if not made measurable

Bridging this gap requires more than improved chemistry or modelling. It requires disciplined process control.

Safety Sensitivity
As energy densities increase and new chemistries such as sodium-ion or solid-state cells enter production, tolerance for manufacturing variability decreases. Safety incidents still originate more from process deviations than from design and material choice. Higher performance narrows operating margins. Small errors that were once manageable can become critical.

The gap between proven technology and stable production is therefore not a contradiction. It is a transition. Laboratory validation demonstrates what is possible. Industrial discipline determines what is sustainable.

Europe vs Asia - governance, scar tissue, and tolerance for pain

Global battery expansion is often described as a competitive race. Industry reports compare installed capacity, technology progress, and regional investment momentum. These comparisons are useful but incomplete.

The real differences between regions are less about knowledge than about execution. They reflect what industrial systems are willing, able, or forced to endure in order to achieve operational control. Europe struggles with execution, while Asian countries have earned their position through sustained industrial effort.

High-volume battery manufacturing rewards accumulated experience with instability. Yield loss, equipment drift, safety incidents, and prolonged ramp-up phases create operational scar tissue. Control becomes a learned reflex rather than an abstract objective.

Europe's structural constraints
Europe's battery strategy is shaped by concerns about industrial sovereignty, the protection of automotive value chains, and the desire to reduce dependence on Asian supply networks. However, this ambition unfolds within strict regulatory frameworks, fragmented funding environments, and incomplete control over critical material supply.

Building a competitive ecosystem is difficult when access to anode and cathode precursor materials remains externally dependent. Europe has invested heavily in recycling capacity and circular economy initiatives. Yet much of this infrastructure remains underutilized, with production scrap still representing the primary input stream. This signals that industrial stabilization is still in progress.

Asia's accumulated experience
China and Korea have operated high-throughput battery production over longer time horizons. Through repeated exposure to operational instability, they have developed routines for managing variability across the full process chain. This experience does not eliminate risk. Rapid expansion can create stranded assets if new technologies emerge before existing infrastructure is amortized.
Experience reshapes risk rather than removing it.

The real divider – willingness to pay for control
Modern manufacturing technologies enable connected equipment, traceability, and advanced inspection. In most cases, the constraint is not technological availability but organizational willingness to invest before failure makes the need undeniable.

Inspection and non-destructive testing are frequently postponed because their costs appear high when evaluated in isolation. Their economic value becomes visible only after recalls, audit failures, or safety incidents occur. Adoption, therefore, tends to accelerate under pressure. This pattern is global, but regions differ in how many destabilizing experiences have already shaped institutional memory and decision speed.

Europe contributes governance discipline and long-term strategic framing. Asia contributes scale and operational conditioning. Neither guarantees stable production. Factories can be built in many locations. Competitive durability depends on how effectively variability is controlled once production begins.

Inspection does not eliminate uncertainty.

It defines where uncertainty begins and ends.

Inspection as constraint, not enabler

Inspection does not automatically stabilize production. In fact, it often introduces friction before it creates value. Making inspection effective requires deliberate commitments: to make hidden variability measurable, to shorten feedback loops so that deviations do not accumulate unnoticed, and to expose internal defects before they reach the field. This shifts responsibility from reactive correction to visible operational control.

Control is not a single measure. It must be addressed at multiple levels. Inspection is one of these levels, and one of the most misunderstood.

Why is inspection delayed?
Non-destructive testing is frequently integrated late in a factory's lifecycle. Inspection competes with throughput investments for capital allocation. In thin-margin environments, equipment that increases output is easier to justify than equipment that reduces uncertainty.

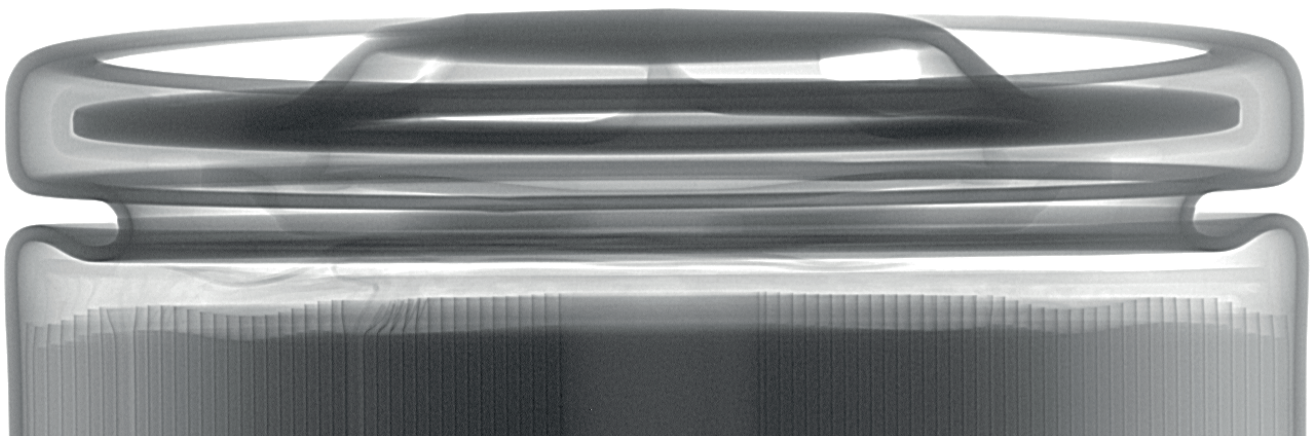
Yet the economics are asymmetric. A few million dollars invested in inspection may appear substantial when evaluated in isolation. The financial impact of late defect detection, recalls, warranty exposure, logistics disruption, and loss of customer trust can be orders of magnitude higher. Inspection, therefore, does not generate revenue - it protects the margin.

Executives who frame inspection investment as risk mitigation rather than overhead are better positioned to evaluate its real contribution. Even simple financial models that compare avoided failure costs, scrap reduction, and inspection operating expense can clarify this trade-off.

In practice, adoption often accelerates only after negative events make the cost of invisibility visible. Retrofitting inspection into scaled production is significantly more disruptive than integrating it during design or ramp-up. Early integration, however, requires committing resources before measurable pain exists.

The throughput tension
Inline inspection is not a plug-in solution. It requires mechanical integration, shielding, data infrastructure, process synchronization, and organizational alignment. The challenge is not whether technologies such as X-ray inspection can detect internal defects. It is whether this capability can be embedded into continuous production without undermining throughput economics. Inspection, therefore, becomes a structural design decision. When treated as an architectural layer, inspection data can inform process adjustments in real time or near real time, accelerating ramp-up and shortening learning cycles. When treated as a discrete quality step, it risks generating undisciplined data accumulation, a liability in high-volume manufacturing.

Inspection does not eliminate uncertainty. It defines where uncertainty begins and ends.



What X-ray solves – and what it does not

X-ray inspection provides insights that are otherwise difficult or impossible to obtain. But it does not perform miracles. Recognizing this boundary is essential for credibility.

Defect detectability depends on multiple technical parameters: X-ray source power, focal spot size, detector sensitivity, imaging geometry, and system integration quality. There is no universal configuration that works across all applications.

Internal features, such as anode overhang in thick cylindrical or prismatic cells, can be reliably visualized in real production environments. High-density foreign particles, such as iron or copper, can be detected at smaller sizes than lower-density inclusions such as aluminum. These limits are defined by physical attenuation and image contrast, not by marketing positioning.

What X-ray inspection can reveal
In practical production contexts, X-ray inspection can provide visibility into:

- Electrode alignment and overhang
- Stacking precision
- Weld penetration and seam integrity
- Internal deformation

What X-ray inspection cannot solve
X-ray inspection does not:

- Stabilize coating, stacking, or winding processes
- Compensation for inconsistent material quality
- Eliminate operator-induced variability
- Replace disciplined process engineering

Careful engineering remains necessary, including appropriate selection and configuration of inspection systems. There is no single solution that fits all cell formats, thicknesses, materials, or production architectures.

Reducing uncertainty, not eliminating it
The real value of X-ray inspection lies in reducing uncertainty. When internal geometry becomes measurable, root-cause analysis accelerates, and process adjustments can be targeted more effectively. Early defect visibility can shorten ramp-up phases, but only if inspection data is integrated into corrective feedback loops. If inspection remains isolated from process stabilization, it becomes documentation rather than control.

The risk of misuse
Inspection can fail through both overestimation and underestimation. Overestimation assumes unlimited internal visibility and ignores constraints such as penetration limits, resolution trade-offs, and reconstruction artifacts. Underestimation leads to dismissing X-ray as unnecessarily complex or expensive compared to optical inspection.

Industrial CT is powerful but bounded. Configuration choices are therefore critical. Applying two-dimensional radiography where volumetric reconstruction is required may leave key defect classes undetected. The result is not improved control, but false confidence.

Comet between industries - strengths, gaps, and responsibilities

Comet X-ray does not deliver complete battery inspection systems. It develops and supplies X-ray modules that system integrators and OEM partners embed within broader inspection architectures. Production outcomes are shaped by the entire inspection chain, including mechanics, shielding, automation interfaces, software integration, and data interpretation.

Our role is to enable inspection capability. We do not own the full production outcome. Comet's contribution lies in the performance and reliability of core imaging components rather than end-to-end system responsibility.

Cross-industry experience – asset and limitation
Comet's engineering heritage spans aerospace, automotive, electronics, and other industrial non-destructive testing. These environments have shaped a development culture focused on uptime, repeatability, and lifecycle durability.

In high-volume battery production, such characteristics are not secondary. Long-standing customers value X-ray sources that operate reliably for years beyond initial expectations. Predictable uptime directly supports production economics.

Cross-industry experience can also help clarify specifications in emerging applications where battery manufacturers may still be defining inspection requirements. However, breadth is not automatically an advantage. Battery production introduces constraints that differ from traditional industrial imaging contexts, particularly the need for deep integration with automation, high-throughput operation, and accelerated scale-up timelines.

Sustained focus and long-term resource allocation toward battery-specific challenges remain ongoing organizational priorities.

Application diversity and portfolio boundaries
Battery manufacturing does not present a uniform inspection problem. Cell formats, material combinations, and dominant defect mechanisms vary significantly across applications. There is no single battery inspection requirement, and no universal inspection solution.

While X-ray sources can often be standardized at the component level, system performance is ultimately defined by factory architecture and cell design.

An honest positioning also requires recognition of portfolio limits. Low-voltage applications, such as electrode basis weight measurement, are not a primary strength of Comet's offering. Instead, the company's capabilities are strongest in higher-energy inspection contexts, for example, penetration of thick cylindrical or prismatic cells in both, laboratory CT analysis and high-power inline detection of foreign particles under industrial uptime requirements.

From hardware excellence to production expectations
Comet's identity remains rooted in equipment engineering. Building high-performance X-ray sources is embedded in the company's DNA. However, battery manufacturers increasingly evaluate suppliers on integration maturity, lifecycle reliability, and responsiveness within continuous 24/7 production environments.

Today, Comet does not typically provide direct gigafactory-level service coverage. Support is delivered primarily through OEM partners and system integrators. This model emphasizes robust product design, diagnostic transparency, and ease of integration to enable effective downstream service. As inspection becomes more structurally embedded in production, expectations toward component suppliers may evolve, particularly regarding shared accountability for visibility and operational continuity.

Conclusion

If one insight remains, it is this: battery manufacturing is no longer primarily a question of chemistry or installed capacity. It is a question of control.
The industry has entered a phase in which scale alone no longer guarantees durability. Installed capacity can be announced and measured. Sustained yield under operational pressure cannot.

Across production environments, the same pattern is visible. Small uncertainties that appear manageable at pilot scale multiply at gigafactory volume. Contamination, misalignment, or delayed feedback do not cause immediate failure. They create prolonged instability. Manufacturing failure is rarely about missing ambition. It is about uncertainties multiplying at scale.

This shift changes the role of inspection. Inspection does not stabilize production on its own. It defines the boundary of visibility. Technologies such as X-ray provide insights that would otherwise remain inaccessible, but they do not replace disciplined engineering or eliminate variability.

The strategic distinction lies in timing. Inspection integrated during ramp-up distributes the cost of learning. Inspection introduced after exposure concentrates risk under pressure.

As consolidation accelerates, competitive advantage will depend less on expansion speed than on operational discipline. Facilities that achieve predictable yield, controlled defect propagation, and resilient production systems will form the durable core of the market. Others may remain in extended ramp conditions, with capital tied up and uncertainty only partially understood.

For suppliers, the implication is equally structural. Hardware performance remains essential, but integration maturity, lifecycle reliability, and shared responsibility for visibility are becoming decisive.

Control will rarely be celebrated as innovation. Yet without it, scale remains fragile, and at the gigafactory level fragility can become an economic disaster.



The Xplorer is a good match for inline production of many smaller battery types as the kV needed for these batteries is in the 110-150kV range with a resolution of around 10-50 microns. Sealed microfocus is the 'bread and butter' of the small battery types in production environments.



The MesoFocus is a great match for inline production for most battery types, including large and dense cells. The MesoFocus is also ideal for inline CT due to dose stability and limited focal spot drift. Most battery applications, as of now, require 25+ micron resolution, which is right in the Meso wheelhouse. The MesoFocus system comes in 225kV and 450kV versions which support high throughput production and gives the ability to perform CT on thicker cells and even battery modules.

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