International Journal of Emerging Research in Engineering and Technology
Pearl Blue Research Group | Volume 7 Issue 4 PP 52-60, 2026
ISSN: 3050-922X | https://doi.org/10.63282/3050-922X.IJERET-V7I4P106

Original Article

An Integrated Risk and Quality Management Framework for Utility-Scale Energy Storage Systems

Neelamegam Subramanian
Independent Researcher, Dublin, USA.

Received On: 28/08/2026 ***Revised On: 24/09/2026*** ***Accepted On: 02/10/2026*** ***Published On: 08/10/2026***

Abstract - *the rapid growth of artificial intelligence (AI), hyperscale data centers, and grid modernization has significantly increased the demand for utility-scale Battery Energy Storage Systems (BESS), positioning them as critical infrastructure for ensuring reliable, resilient, and flexible power delivery. As deployment schedules accelerate, manufacturers face the dual challenge of meeting aggressive production timelines while maintaining stringent quality and safety standards. Conventional quality assurance practices often rely on sequential inspections and testing by stages, which can extend production lead times and identify defects only after substantial value has been added to the product. This paper proposes an Integrated Risk and Quality Management Framework (IRQMF) for utility-scale Battery Energy Storage Systems that implants proactive risk identification and quality assurance throughout the product lifecycle. The framework combines risk assessment methodologies, including Failure Modes and Effects Analysis (FMEA), Critical-to-Quality (CTQ) characteristics, Statistical Process Control (SPC), supplier quality management, process validation, and closed-loop feedback mechanisms to detect and mitigate potential failures before they propagate through manufacturing, integration, and deployment. By shifting quality activities upstream and integrating risk intelligence across design, supply chain, manufacturing, testing, commissioning, and field operations, the proposed framework aims to reduce quality escapes, optimize testing strategies, shorten production lead times, and improve product reliability. The proposed approach provides manufacturers with a scalable methodology for balancing speed, quality, and operational resilience in an era of unprecedented demand for energy storage infrastructure. It also establishes a foundation for future integration of predictive analytics, digital quality systems, and artificial intelligence to further enhance defect prevention and continuous quality improvement across the BESS lifecycle.*

Keywords *- Battery Energy Storage Systems, Quality Assurance, Risk Management, FMEA, SPC.*

1. Introduction

The global energy landscape is undergoing one of the most significant transformations in recent decades. Electrification across transportation, industrial operations, and digital infrastructure has accelerated electricity demand beyond historical planning assumptions. In particular, the rapid adoption of electric vehicles (EVs), the expansion of renewable energy resources, and the unprecedented growth of artificial intelligence (AI)-enabled hyperscale data centers have substantially increased the need for reliable, flexible, and dispatchable energy resources. Utilities that previously projected modest annual load growth are now revising long-term forecasts as large industrial loads and AI computing facilities place increasing pressure on existing transmission and generation capacity. Recent industry reports indicate that data center-driven electricity demand is becoming a major driver of utility investment, grid modernization, and energy storage deployment. [1]– [3].

Battery Energy Storage Systems (BESS) have emerged as a foundational technology for supporting grid reliability, renewable energy integration, peak demand management, and backup power for critical infrastructure. Utility-scale BESS installations enable grid operators to improve system resilience, mitigate intermittency associated with renewable generation, and respond rapidly to dynamic load conditions. Consequently, energy storage is transitioning from a supplementary grid asset to a critical infrastructure component whose availability directly influences project schedules, grid stability, and the commissioning of new industrial facilities and data centers.

The increasing strategic importance of BESS has created unprecedented demand. The International Energy Agency projects that global data center electricity consumption will increase from approximately 485 TWh in 2025 to around 945 TWh by 2030, largely driven by AI workloads [1], [2]. The U.S. Department of Energy estimates that total U.S. electricity demand could increase by 15–20% over the next decade, reversing nearly two decades of relatively flat growth. AI, domestic manufacturing, electrification, and transportation are the primary drivers [4] Utilities, independent power producers, renewable energy developers, and technology companies are simultaneously deploying large-scale storage assets, resulting in compressed delivery schedules and growing pressure on manufacturers to increase production capacity. At the same time, shortages of critical electrical equipment, long component lead times, supply chain constraints, and manufacturing bottlenecks have extended project schedules across the energy sector, making timely delivery a competitive differentiator.

While manufacturing capacity has expanded considerably, ensuring product quality at scale remains a significant engineering challenge. Utility-scale BESS products integrate thousands of electrochemical cells, battery management systems, power conversion equipment, thermal management systems, manifolds transporting fluids, high-voltage electrical assemblies, wiring harness, mechanical structures, software controls, and safety protection mechanisms into a highly complex system. A defect introduced during any stage of design, supplier manufacturing, module assembly, system integration, testing, transportation, installation, or commissioning can propagate downstream, increasing rework costs, delaying customer deliveries, or compromising long-term system reliability.

Conventional quality assurance methodologies in manufacturing are predominantly driven by stages, relying on inspections and validation activities performed independently at discrete phases of the product lifecycle. Although these approaches have historically improved product quality, they often detect failures only after substantial manufacturing effort and material costs have already been incurred. As production volumes increase and deployment schedules compress, late-stage defect discovery contributes to manufacturing inefficiencies, extended lead times, repeated testing cycles, quality escapes, and delayed field deployment. Furthermore, quality information generated during supplier qualification, manufacturing, factory acceptance testing, transportation, site installation, and commissioning frequently remains fragmented across organizational functions, limiting proactive decision-making and reducing the effectiveness of risk mitigation.

The growing complexity of utility-scale BESS manufacturing necessitates a transition from reactive quality inspection toward proactive, risk-informed quality management. Rather than treating quality assurance as a sequence of independent verification activities, manufacturers require an integrated framework that continuously identifies, evaluates, and mitigates quality risks throughout the entire product lifecycle. Early identification of potential failure modes enables engineering teams to prioritize preventive actions before defects propagate into downstream manufacturing processes or field installations, thereby reducing quality escapes, improving production throughput, and enhancing overall system reliability.

This paper proposes an Integrated Risk and Quality Management Framework (IRQMF) for Utility-Scale Battery Energy Storage Systems. The framework integrates established quality engineering methodologies—including Failure Modes and Effects Analysis (FMEA), Critical-to-Quality (CTQ) characteristics, Statistical Process Control (SPC), supplier quality management, process validation, reliability engineering, and closed-loop quality feedback—within a unified risk-driven decision framework spanning design, supply chain, manufacturing, testing, commissioning, and field operations. By embedding continuous risk assessment throughout the product lifecycle, the proposed framework seeks to improve defect prevention, optimize quality assurance activities, reduce manufacturing lead times, and support the accelerated deployment of utility-scale energy storage systems required to meet the rapidly growing global demand for resilient electrical infrastructure.

2. Literature Review – Related Work in Industry

2.1. Existing Quality Management Approaches in Battery Manufacturing

Currently quality assurance methodologies that are employed in battery manufacturing primarily focus on process compliance, inspection planning, statistical monitoring, and end-of-line verification. Automotive battery manufacturing has matured around standards such as IATF 16949, ISO 9001, AIAG Core Tools, and Advanced Product Quality Planning (APQP). These frameworks provide structured methodologies for process development, capability analysis, supplier management, and continuous improvement. Traditional quality management systems in manufacturing, such as those governed by ISO 9001, rely on prevention-based planning frameworks including Advanced Product Quality Planning (APQP) and the Production Part Approval Process (PPAP) [5]–[7]. These frameworks, originally developed within the automotive supply chain, establish structured checkpoints at which design intent, process capability, and part conformance are verified before a supplier is authorized for full-rate production. Complementing APQP/PPAP, Failure Modes and Effects Analysis (FMEA), as codified in the AIAG & VDA FMEA Handbook, provides a structured method for identifying potential failure modes and evaluating their severity, occurrence, and detectability so that corrective actions can be prioritized before failures occur [5]. Statistical Process Control (SPC), introduced by Shewhart in the 1920s and formalized in reference texts such as Montgomery's Introduction to Statistical Quality Control, remains the primary method for distinguishing common-cause from special-cause variation in manufacturing processes [6].

While these approaches have significantly improved manufacturing quality, they were primarily developed for high-volume automotive production environments where production schedules and product architectures are relatively stable. Utility-scale Battery Energy Storage Systems introduce substantially different operational challenges, including customized project configurations, multi-supplier integration, higher system complexity, stringent grid compliance requirements, and compressed deployment schedules.

Consequently, traditional quality assurance methodologies often lack mechanisms for integrating real-time manufacturing risks with enterprise-wide decision-making across suppliers, system integration, logistics, commissioning, and field operations.

2.2. Quality and Safety Considerations Specific to BESS

Utility-scale BESS present quality and safety challenges that differ materially from many conventional manufactured goods because of the electrochemical, electrical, and thermal hazards associated with large-format lithium-ion cells. A substantial amount of literature has examined thermal

runaway propagation mechanisms, early-warning detection, and mitigation strategies for lithium-ion battery systems [13]–[16]. In parallel, the safety and testing standards landscape has matured considerably: IEC 62619 defines safety requirements for secondary lithium cells and batteries used in industrial applications [9], while UL 9540A provides the large-scale fire test method referenced by NFPA 855, the U.S. standard governing the installation of stationary energy storage systems [10], [11].

Perhaps most directly relevant to the present work, EPRI's BESS Failure Incident Database has tracked publicly reported BESS failure events since 2018 and found that the failure rate per gigawatt of BESS deployed declined by approximately 99% between 2018 and 2023—from roughly 9.2 to 0.2 events per GW—a trend attributed largely to lessons learned being incorporated into design, manufacturing, and installation practice [12]. The same analysis found that "integration, assembly, and construction," rather than cell or module defects considered in isolation, was the single largest root-cause category among the failure events for which sufficient information was available to assign a cause [12]. This finding implicates system-level integration and quality assurance practice—rather than component quality alone—as a primary determinant of field reliability, and directly motivates a framework, such as the one proposed here, that treats quality as a property of the entire lifecycle and supply chain rather than a series of discrete component checks

3. Path towards Data-Driven and Predictive Quality Management

Beyond established quality engineering tools, a growing body of "Quality 4.0" literature examines how digital twins, real-time process monitoring, and machine learning can be integrated into manufacturing quality systems to enable predictive—rather than purely reactive—quality management [17], [18]. These approaches promise reduced inspection burden, earlier detection of process drift, and tighter closed-loop feedback between field performance and upstream design and manufacturing decisions. However, the Quality 4.0 literature has focused primarily on discrete manufacturing and general industrial contexts; its application to the specific reliability, safety, and lifecycle characteristics of utility-scale BESS remains comparatively underdeveloped. This paper positions the proposed IRQMF as a structured foundation onto which such predictive and data-driven capabilities can subsequently be layered.

4. GAP that is addressed by this Paper

Collectively, the literature demonstrates mature, independently well-established tools for risk identification (FMEA), process control (SPC), supplier qualification (APQP/PPAP), and safety certification (UL 9540A, IEC 62619, NFPA 855), together with emerging evidence that system integration—rather than isolated component failure—dominates the observed BESS field-failure profile [12]. What remains comparatively absent is an integrated framework that (i) explicitly links these tools across the full BESS product lifecycle, (ii) is tailored to the specific system architecture and failure modes of utility-scale BESS, and (iii) establishes closed-loop feedback pathways connecting field performance data back to design and manufacturing decisions. This paper addresses that gap.

5. Sources of Quality Risk Items in Utility Scale BESS

To define a utility-scale BESS is not a single product but a system-of-systems, integrating electrochemical, electrical, thermal, mechanical, and software subsystems supplied by multiple vendors and assembled across several physical locations before final commissioning at a customer site. Table I summarizes representative subsystems and their principal quality and risk domains. The breadth of this table illustrates why a single-stage or single-function quality approach is structurally insufficient: a defect risk introduced in electrical balance-of-plant workmanship, for example, is not meaningfully addressed by cell-level incoming inspection, and vice versa. Effective quality assurance for utility-scale BESS must therefore span subsystem boundaries and organizational functions, which is the central premise of the framework proposed in Section VI.

Table 1: BESS Subsystem Complexity and Associated Quality Risks

Subsystem	Components	Primary Quality Risk items
Electrochemical cells & modules	Li-ion cells, module enclosures, interconnects, busbars	Cell-to-cell variability, weld/ interconnect integrity, thermal runaway propagation
Battery Management System (BMS)	Cell monitoring boards, module/rack controllers, firmware	Sensor accuracy, communication faults, firmware version control, SOC/SOH estimation error
Power Conversion System (PCS)	Inverters, transformers, switchgear	Power electronics reliability, grid-code compliance, thermal cycling fatigue
Thermal management	HVAC units, liquid cooling loops, coolant, sensors	Coolant leaks, temperature uniformity, moisture ingress
Fire detection & suppression	Smoke/gas detectors, suppression agent, deflagration venting	Detection latency, suppression activation reliability, enclosure venting design
Mechanical / enclosure	Containers, racking, seismic bracing, gaskets	Ingress protection (IP) rating, structural integrity, corrosion
Controls & software	EMS/SCADA integration, protection relays	Cybersecurity, software regression defects, integration faults

6. Proposed Integrated Risk and Quality Management Framework (IRQMF)

6.1. Design Principles

The IRQMF is organized around four design principles. First, risk identification: quality-critical decisions are made as early as design and supplier selection, rather than deferred to inspection and test. Second, risk-proportionate resource allocation: testing intensity, sampling rates, and audit frequency are scaled to the severity and detectability of the associated failure mode rather than applied uniformly. Third, cross-functional data integration: risk and quality information generated by engineering, supply chain, manufacturing, test, and field service functions is captured in a shared system of record rather than siloed within each function. Fourth, closed-loop feedback: field and test performance data are systematically routed back to design and process owners to drive corrective and preventive action (CAPA), so that the framework improves continuously rather than functioning as a static checklist.

6.2. Framework Architecture

Figure 1 depicts the overall architecture of the IRQMF. The framework is organized in three layers. The top layer represents the physical product lifecycle stages—design and engineering, supply chain and supplier qualification, manufacturing and assembly, testing and verification, commissioning, and field operations. The middle layer maps specific risk and quality methodologies to each lifecycle stage: Design FMEA (DFMEA) and risk identification at the design stage; CTQ flow-down and APQP/PPAP at the supply chain stage; Process FMEA (PFMEA) and process validation during manufacturing; SPC and risk-based test strategy during testing; acceptance criteria and verification at commissioning; and field data collection and failure analysis during operations. The bottom layer is a digital quality backbone—a shared risk register, traceability system, and cross-functional governance structure—that underpins the other two layers and provides the data foundation for the closed-loop feedback path and for future predictive-analytics capability (Section VII).

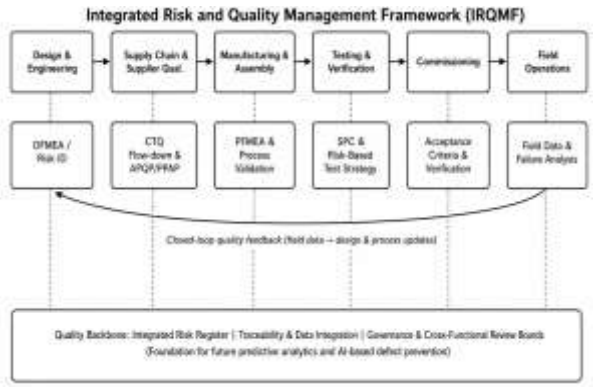


Fig 1: IRQMF Conceptual Architecture: Lifecycle Stages (Top), Mapped Risk/Quality Methodologies (Middle), and the Digital Quality Backbone with Closed-Loop Feedback (Bottom)

6.3. Risk-Informed Quality Flow

Figure 2 presents the framework as a process flow, emphasizing the sequential dependencies between lifecycle stages and the risk gates positioned between them. At each transition, a risk gate evaluates whether open risk items, out-of-control process signals, or unresolved CTQ non-conformances exist before authorizing progression to the next stage. This gating mechanism is intended to prevent the propagation of undetected defects downstream, consistent with the EPRI finding that integration and assembly issues—many of which are detectable through gated process controls—represent the leading root-cause category of reported BESS failures [12]. The dashed feedback path returns field operations data to the design stage, closing the loop described in Section

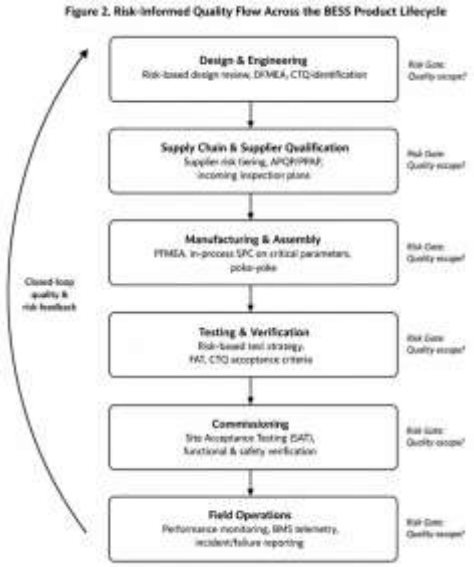


Fig 2: Risk-Informed Quality Flow across the BESS Product Lifecycle, With Inter-Stage Risk Gates and Closed-Loop Feedback from Field Operations to Design

6.4. Risk Based Design Review and PFMEA

At the design stage, cross-functional teams conduct a Design FMEA covering the subsystems identified in Table I, evaluating each candidate failure mode for severity of effect, likelihood of occurrence, and probability of detection prior to shipment. Table II presents an illustrative excerpt of such an analysis for a representative set of BESS failure modes, expressed using the conventional Risk Priority Number (RPN = Severity × Occurrence × Detection); organizations may equivalently adopt the Action Priority (AP) ranking introduced in the AIAG & VDA FMEA Handbook [5]. Failure modes with high severity or high RPN—such as inter-cell weld resistance excursions or BMS sensing faults—are prioritized for design mitigation (e.g., redundant sensing, automated in-line inspection) rather than being addressed solely through downstream testing.

Table 2: Illustrative Risk Assessment Excerpt. Severity/Occurrence/Detection Values are Notional (1–10 Scale) and Intended to Demonstrate the Prioritization Method Rather than to Represent Measured Data from a Specific Product

Failure Mode	Potential Effect	Potential Causes	Rpn (Sev*Occ*Det)	Detection Method	Recomm-Ended Mitigati-On
Inter-cell weld/interconnect resistance out of specification	Localized overheating; accelerated degradation; potential thermal event	Weld parameter drift; electrode surface contamination	108 (9×3×4)	In-process weld resistance test	SPC on weld current/automated weld monitoring
BMS cell-voltage sensing fault	Inaccurate SOC/SOH estimation; delayed fault detection	Connector/harness defect; firmware defect	120 (8×3×5)	FAT communication stress test	Redundant voltage sensing; firmware regression suite
Coolant loop leak	Localized thermal excursion; electrical short risk	Manifold not connected properly	80 (8×2×5)	Pressure-decay leak test	100% pressure-decay test at FAT;
Busbar/terminal torque under-tightening	High-resistance connection; localized heating	Missed torque step; tool miscalibration	84 (7×3×4)	Torque audit / witness marks	Data-logging torque tools; 100% verification with witness marks
Incorrect BMS/EMS firmware version deployed	Unexpected control behavior; protection mismatch	Configuration management error at site	42 (7×2×3)	Commissioning checklist	Automated firmware version verification; configuration control system
Fire suppression false/failed activation	Loss of protection function or nuisance discharge	Detector calibration drift; wiring fault	108 (9×2×6)	Periodic functional test	Redundant detection; UL 9540A-informed design verification

6.5. Critical to Quality (CTQ) Characteristic flow down

CTQ analysis translates customer and regulatory requirements into measurable process parameters and control methods. Table III illustrates this flow-down for a subset of BESS requirements, connecting a high-level requirement (e.g., grid-code compliance, design life) to a specific, monitor able characteristic and the control method used to hold it in-specification. This traceability is essential both for focusing SPC effort on the parameters that matter most and for demonstrating compliance during customer and third-party audits.

Table 3: Example Flow Down From Customer/Regulatory Requirement to Controlled Process Parameter.

Customer / Regulatory Requirement	CTQ Characteristic	Process Parameter
Design life & UL 9540A-informed safety performance	Cell-to-cell temperature variation within module	Thermal management airflow / coolant flow rate
Grid-code compliance (e.g., IEEE 1547)	PCS response time to frequency/voltage events	Inverter control firmware calibration
Personnel and asset safety	Insulation resistance of DC bus	Wire harness assembly & routing
System availability guarantee	BMS communication uptime	Connector/harness quality; EMI shielding
Fire / thermal safety	Inter-cell weld resistance	Welding process parameters (current, force, time)

6.6. Supplier Quality Management

Because BESS integrate components from cell, BMS, PCS, thermal management, and mechanical suppliers, supplier quality management is a first-class element of the framework rather than a peripheral activity. The IRQMF adopts a risk-tiered approach, summarized in Table IV, in which suppliers of safety-related or high-severity components (Tier 1) are subject to full APQP/PPAP qualification, demonstrated process capability ($Cpk \geq 1.33$), and continuous surveillance, while lower-risk commodity suppliers (Tier 3)

are managed through certificate-of-conformance and statistical sampling [7], [8]. This tiering concentrates scarce quality engineering resources on the suppliers and components most likely to drive severe or high-frequency failure modes.

Table 4: Supplier Tier Classification and Corresponding Quality Assurance Requirements

Supplier Tier	Criteria	Required Quality Tasks
Tier 1 — Critical / safety-related	Cells, BMS, PCS, fire suppression	Full APQP, PPAP submission, process capability evidence (Cpk ≥ 1.33), resident quality engineer
Tier 2 — Major subsystem	Thermal management, enclosures, switchgear	Streamlined APQP, PPAP on critical characteristics, incoming inspection sampling plan
Tier 3 — Standard commodity	Fasteners, cabling, brackets	Certificate of conformance; AQL-based statistical sampling

6.7. PFMEA, Process Validation and SPC

During manufacturing, a Process FMEA identifies potential process-induced failure modes (e.g., weld parameter drift, torque under-tightening) and defines corresponding control plans. Critical parameters identified through the CTQ flow-down and PFMEA are placed under Statistical Process Control, using Shewhart-type control charts to distinguish common-cause variation from special-cause signals that require process intervention [6]. Figure 3 shows an illustrative $\bar{X}$ control chart for inter-cell weld resistance, a parameter identified as high-severity in Table II. A drift beyond the upper control limit—as shown toward the end of the illustrated production sequence—triggers an automatic process hold under the risk-gate logic, preventing further potentially non-conforming units from advancing to test. Process validation activities (installation, operational, and performance qualification, analogous to IQ/OQ/PQ practice) confirm that manufacturing and test equipment are capable of holding CTQ parameters within specification before production ramp.



Fig 3: Illustrative $\bar{X}$ Control Chart for a Critical-to-Quality Manufacturing Parameter (Inter-Cell Weld Resistance), Showing a Special-Cause Drift Exceeding the Upper Control Limit

6.8. Risk-Based Test Strategy Optimization

Rather than applying uniform test coverage across all units and characteristics, the IRQMF allocates factory acceptance testing (FAT) depth and sampling frequency in proportion to the RPN/AP ranking established during FMEA and to the demonstrated process capability of the corresponding manufacturing step. Characteristics with high severity and low demonstrated process capability receive expanded or 100% test coverage; characteristics with low severity and high demonstrated process capability—confirmed through sustained SPC performance—are eligible for reduced sampling. This risk-based approach is intended to shorten overall test duration without increasing the probability of a quality escape, addressing the lead-time pressure while preserving—and in high-risk areas increasing—effective defect detection.

6.9. Commissioning and Closed-Loop Field Feedback

At commissioning, Site Acceptance Testing (SAT) verifies functional and safety performance under actual site conditions, including configuration and firmware version verification (Table II) to guard against configuration-management errors identified as a credible failure mode. Following commissioning, field operations data—BMS telemetry, performance monitoring, and incident or failure reports—are captured and routed back into the shared risk register. Figure 4 depicts this closed loop as a continuous cycle of risk identification, assessment and prioritization, mitigation, monitoring, and verification with captured learning, mirroring the plan-do-check-act logic underlying CAPA systems. This closed loop is the mechanism by which field experience—such as the integration-related failure modes identified in EPRI's incident database [12]—is systematically fed back into design reviews and process control plans for subsequent production, rather than being addressed only on a unit-by-unit basis.

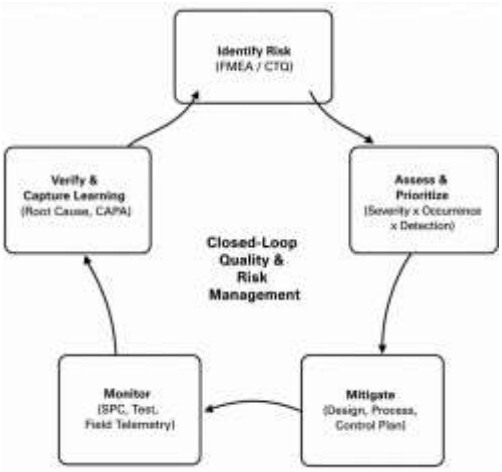


Fig 4: Closed-Loop Quality and Risk Management Cycle Connecting Field and Test Data Back to Design and Process Controls

6.10. Digital Quality Backbone

Underpinning all lifecycle stages is a digital quality backbone: a shared risk register linking DFMEA/PFMEA entries, CTQ characteristics, SPC data, supplier quality records, test results, and field incident reports through common part, serial, and lot identifiers. This traceability layer does not itself perform predictive analytics, but it establishes the structured, integrated dataset that is a prerequisite for the machine-learning-based defect prediction. In this sense, the IRQMF is deliberately structured as a foundation for future analytical capability rather than a terminal state.

7. Example Application – Inter-Cell Weld Failure Scenario.

To illustrate the practical effect of the framework, consider the inter-cell weld/interconnect failure mode identified in Table II—selected because weld and interconnect integrity is directly linked to thermal-runaway risk and because integration-related issues are the leading documented root cause of reported BESS field failures [12]. Table V compares, stage by stage, when this defect would plausibly be detected under a traditional sequential QA approach versus under the IRQMF. Under sequential QA, because no formal DFMEA prioritizes the weld interconnect and inspection relies on end-of-line sampling, an out-of-specification unit has a realistic chance of passing FAT and being discovered only after commissioning, when the value invested in the unit—and the cost and schedule impact of remediation—is at its highest. Under the IRQMF, the same failure mode is flagged during design as a high-severity CTQ, placed under 100% in-line SPC during manufacturing, and, in the event a signal is missed, is caught by expanded risk-based FAT sampling before shipment. This scenario is illustrative rather than empirical; it is intended to demonstrate the mechanism by which the framework is expected to shift defect detection upstream, consistent with the quality-escape reduction and lead-time objectives

Table 5: Stage-By-Stage Comparison of Defect Detection under Traditional Sequential QA versus the IRQMF for A Representative Weld/Interconnect Failure Mode

Lifecycle stage	Traditional QA	IRQMF
Design	No formal DFMEA on weld interconnect	DFMEA flags weld resistance as a high-severity CTQ; SPC control plan defined pre-production
Manufacturing	Weld inspected via end-of-line sampling only	100% in-line SPC monitoring; automatic process hold on out-of-control signal
Testing	Defect may pass FAT if outside sampled units	Risk-based test plan increases sampling intensity on high-RPN characteristics
Commissioning / field	Defect discovered as a thermal event or performance degradation post-commissioning	Defect contained pre-shipment; if missed, field telemetry and closed-loop feedback route root cause back to design/process rapidly
Value at risk when discovered	High — full system built, shipped, and installed	Low — caught at in-process or incoming stage

7. Expected Benefits, Enablers and Limitations

7.1. Expected Benefits

Table VI summarizes the framework-level differences between traditional sequential QA and the proposed IRQMF across seven dimensions. The expected benefits follow directly from these structural differences: earlier defect detection reduces the manufacturing value invested in non-conforming units at the point of discovery; risk-based test allocation is expected to reduce redundant testing on low-risk, high-capability characteristics while increasing scrutiny on high-severity characteristics, shortening average test duration without degrading detection effectiveness; risk-tiered supplier management concentrates qualification effort where it has the greatest expected impact on field reliability; and closed-loop feedback shortens the interval between a field or test observation and a corresponding design or process change. These expected benefits are directionally consistent with the industry-observed decline in BESS failure rates as quality assurance and monitoring practices have matured [12], though the magnitude of benefit for any specific manufacturing operation depends on baseline process maturity and is a subject for future empirical validation.

Table 6: Summary comparison of traditional sequential quality assurance and the proposed Integrated Risk and Quality Management Framework

Attribute	Traditional QA	Irqmf
Timing of quality activities	Predominantly end-of-stage inspection	Continuous, embedded from design through field operations
Risk prioritization	Ad hoc or uniform testing intensity	Severity/occurrence/detection-based prioritization (FMEA-driven)
Supplier oversight	Incoming-inspection-focused	Risk-tiered APQP/PPAP-based qualification and surveillance
Data integration	Siloed by function and lifecycle stage	Shared digital risk register and end-to-end traceability
Feedback to design	Slow, informal, often lost	Structured closed-loop CAPA process

Test strategy	Fixed test plan regardless of risk level	Risk-based, optimized sampling and coverage
Primary failure detection point	Late (FAT, commissioning, or field)	Early (design review, in-process SPC)

7.2. Organizational Enablers

Successful implementation of the IRQMF depends on strong commitment from leadership, an empowered cross-functional risk review board with authority to hold production pending disposition of high-severity findings; training of manufacturing and quality personnel in FMEA, SPC, and root-cause analysis methods; a change-management process that keeps DFMEA/PFMEA documents synchronized with actual design and process revisions; and, especially for scale-up operations, investment in the digital quality backbone so that risk, process, and field data are captured in a common, traceable system rather than in disconnected spreadsheets and paper travelers.

7.3. Limitations and Implementation Challenges

Several limitations warrant acknowledgment. First, the FMEA-based prioritization used throughout the framework relies on engineering judgment for severity, occurrence, and detection ratings; while structured facilitation and historical field data (e.g., from Table VI's feedback loop) can calibrate these ratings over time, early-stage assessments necessarily carry estimation uncertainty. Second, risk-tiered supplier management and expanded in-line SPC require upfront investment in tooling, instrumentation, and personnel training that may be difficult to justify for lower-volume or early-stage manufacturers. Third, the framework as presented is descriptive and illustrative rather than validated against a controlled before/after production dataset represent expected mechanisms rather than measured outcomes, and empirical validation using production data from an operating BESS manufacturing line is an important direction for future work. Finally, cross-functional data integration can be organizationally difficult where design, supply chain, manufacturing, and field service functions operate on separate legacy systems; realizing the full closed-loop benefit of the framework may require phased system integration rather than a single implementation step.

8. Future work

The digital quality backbone is designed as a foundation for several extensions. First, predictive quality analytics: machine-learning models trained on the integrated DFMEA/PFMEA, SPC, test, and field dataset could forecast the probability of a quality escape for a given production lot before it reaches test, enabling further risk-based optimization of test coverage. Second, digital twins of manufacturing and field assets could simulate the propagation of an observed process deviation (e.g., a weld parameter drift) through to expected field performance, supporting earlier and more quantitative disposition decisions; industry evidence from broader Industry 4.0 deployments suggests digital twins can materially reduce lead times and increase throughput in comparable manufacturing contexts [17], [18]. Third, automated anomaly detection on BMS telemetry could shorten the closed-loop feedback interval described in Section IV-I from a manual, periodic review to near-real-time detection of emerging field failure modes. Finally, empirical validation of the framework—through pilot deployment on an active BESS production line with before/after tracking of quality escape rate, test duration, and lead time—is required to move the benefits from expected mechanism to measured outcome.

9. Conclusion

This paper has proposed an Integrated Risk and Quality Management Framework (IRQMF) for utility-scale Battery Energy Storage Systems, motivated by the accelerating demand for BESS driven by AI-enabled data center growth and broader grid modernization, and by evidence that system integration—rather than isolated component failure—is the leading documented root cause of reported BESS field failures. Rather than relying on sequential, stage-gated inspection, the IRQMF embeds risk identification and mitigation continuously across design, supply chain, manufacturing, testing, commissioning, and field operations, using an integrated combination of DFMEA/PFMEA, CTQ flow-down, risk-tiered supplier quality management, Statistical Process Control, risk-based test strategy, and closed-loop field feedback, all underpinned by a shared digital quality backbone. The framework is intended to shift defect detection upstream, concentrate quality engineering resources on the highest-severity risks, and shorten the feedback interval between field experience and design or process improvement—addressing the dual pressure manufacturers face to accelerate delivery while sustaining the safety and reliability performance that utility-scale energy storage infrastructure demands. The framework as presented is descriptive; the illustrative examples in Sections IV and V are intended to demonstrate its mechanisms rather than to substitute for empirical validation. Future work applying the framework to production data, and extending its digital quality backbone with predictive analytics and digital-twin capability, is expected to further strengthen its contribution to reliable, at-scale BESS manufacturing.

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