WEBINAR

BESS manufacturing quality: Lessons learned from more than 30GWh of factory inspections

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CEA
CLEAN ENERGY ASSOCIATES

Energy Storage NEWS

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Lessons Learned From 30+ GWh BESS Quality Inspection

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Lessons Learned From 30+ GWh BESS Quality Inspection

1. Company and service overview
2. Multi-faceted approach to ESS safety and performance
3. Quality data from 30+ GWh track record
4. Case studies

1

Company and Service Overview

Company Snapshot

Clean Energy Associates is a technical advisory company, under Intertek, that provides unrivaled insight into the solar PV, energy storage, and electrolyzer manufacturing industries to ensure the success of projects worldwide.

1,000+
Years of industry experience

225+
Professionals

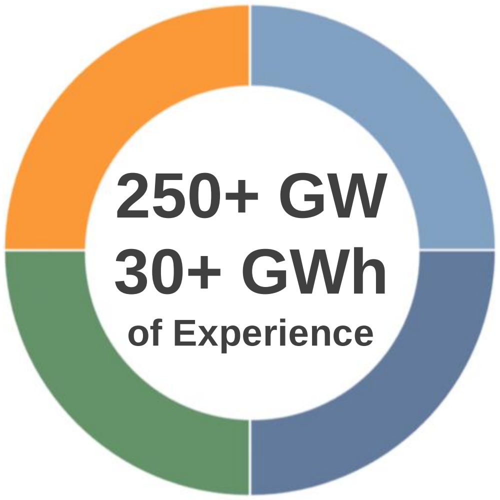
150+
Engineers

15
Year track record

15
Countries with a physical presence

Supply Chain Management

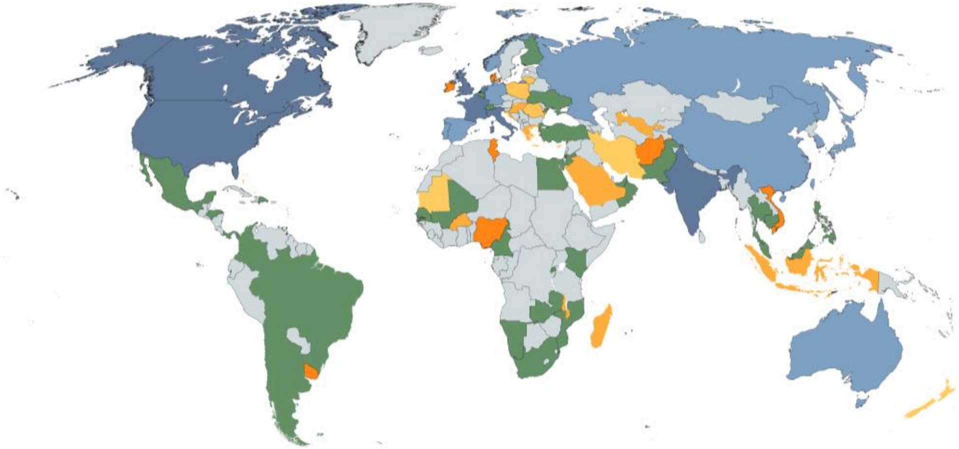
Market Intelligence



Engineering Services

Quality Assurance

Client engagements in **75+** countries



Engagements in **350+** solar and storage factories worldwide

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Quality Assurance (QA) Service Overview

CEA performs Quality Assurance work before, during, and after the production throughout different levels and types of ESS, including cell, module, rack, enclosure, containerized system as well as residential ESS, performing four (4) main auditing activities:

Factory Audit (FA)	• A team of engineers audit a factory location using a 300+ points checklist • Both quality systems and quality process are audited • Findings are recorded and classified according to its risk assessment • Corrective actions are suggested and followed through.
Inline Production Monitoring (IPM)	• A team of engineers continuously monitor the manufacturing process of a factory location during the production of an order, using independent checklists for different workshops including cell, module, rack, and system • Production processes and inline quality control are monitored • Findings are recorded and classified according to its risk assessment • Corrective actions are suggested and followed through.
Pre-Shipment Inspection (PSI)	• A team of engineers perform visual inspection and performance & functional tests to a randomly selected lot of finished products (cell, module and rack), according to a list of vetted quality criteria • Only finished products are audited • Findings are recorded and classified according to its risk assessment • Corrective actions are suggested and followed through.
Factory Acceptance Test (FAT)	• A team of engineers perform visual inspection, performance & functional tests and mechanical tests to a randomly selected lot of finished products (containerized ESS and residential ESS), according to a list of vetted quality criteria • Only finished products are audited • Findings are recorded and classified according to its risk assessment • Corrective actions are suggested and followed through

50+
factories has been audited by CEA globally.

30+ GWh
total executed project volume.

360+
quality inspections.

1300+
total findings in multiple BESS QA services.

2

Multi-faceted Approach To ESS Safety & Performance

What Can Go Wrong?

The intricacies in BESS product design, uncertainties in battery supply chain, laxness in quality control execution, and complex use cases during in-field operation create room for failure in terms of safety, reliability, and performance.

1 Product Design Validation

Battery design “black boxes”:

- Thermal management system’s effectiveness in maintaining ideal operating temperature
- Balancing strategy’s effectiveness in maintaining system energy retention
- Risk assessment’s correlation with design considerations

2 Project Procurement

Supply chain uncertainties:

- Supplier’s manufacturing capability and the ability to meet product development milestones and delivery deadlines
- Completeness of supplier’s quality assurance systems and testing protocols to ensure product reliability and performance

3 Product Mass Production

Quality control execution laxness:

- Lengthy cell production processes are vulnerable to quality issue despite of high level of automation
- Highly manual system integration processes pose quality and under performance

4 In-field Operation

Maximizing revenue without consideration on physical limitations:

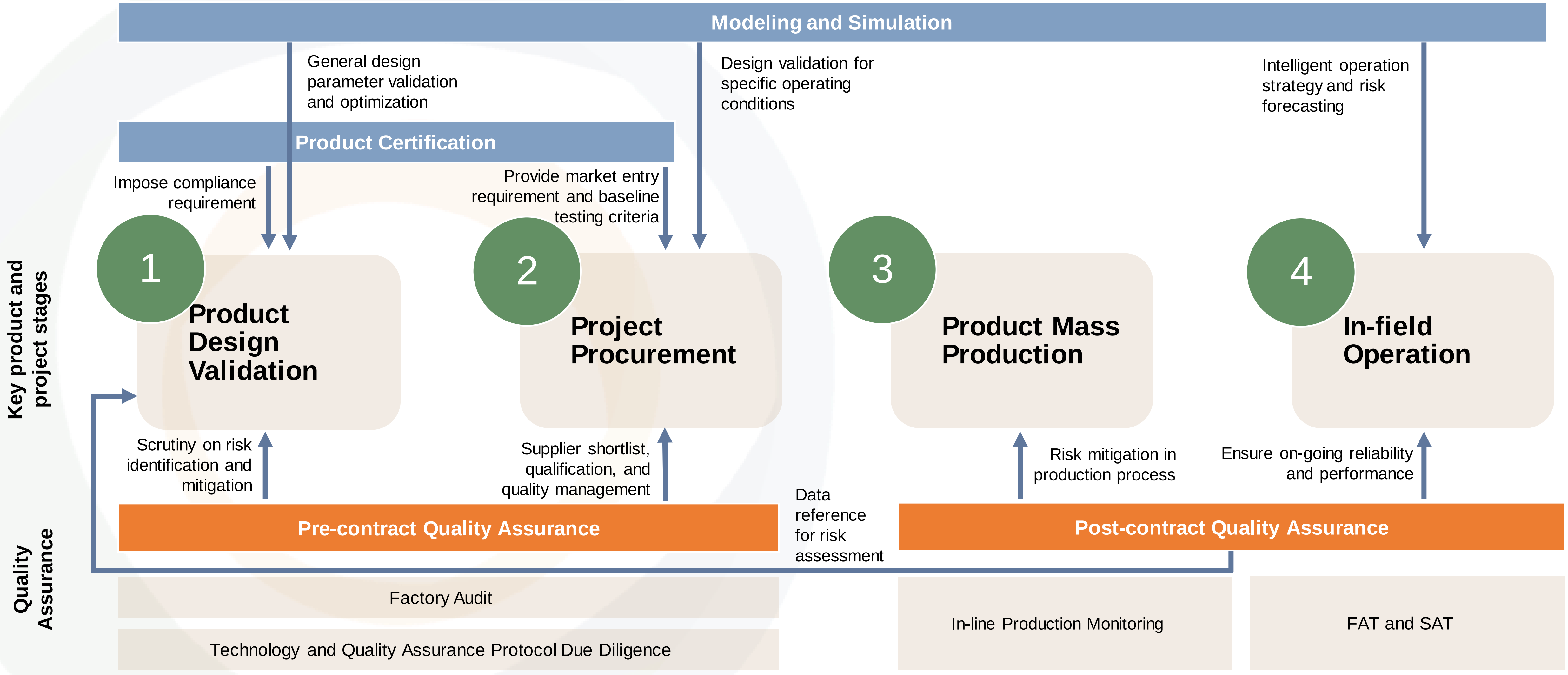
- The real degradation in specific project environment and all potential use cases is difficult to forecast
- Capacity and performance inconsistency stemming from manufacturing defects can manifest during in-field operation.

Multi-faceted Approach to Safety & Performance

Among various tools to ensure battery safety and performance, quality assurance is the most efficient mean to mitigate risks during mass production.

CEA Services

Other Approaches



What Can Be Done? - Thermal Runaway Risk Mitigation

	McMicken April 2019	Victorian Big Battery July 2021	Moss Landing Phase I & II September 2021 & February 2022	Elkhorn September 2022
Root cause and contributing factors	➢ Internal failure in a battery cell from dendrite growth ➢ Incapable FSS without effective means to ventilate flammable gases ➢ Lack of thermal barriers between cells	➢ Short circuiting of electronic component from coolant leakage ➢ Disabled telemetry, thermal management, and protection systems from a key lock	➢ Water sprinkler system was triggered below the designed smoke level (Phase I) ➢ Faulty Emergency-Stop function failed to stop the sprinklers system. (Phase I) ➢ A leaking hose caused the suppression system to release water on battery racks causing them to short (Phase II)	➢ Electrical short from significant water ingress ➢ Automatic safe discharge (ASD) feature was not implemented in the firmware ➢ Failed isolation failure alert from outdated firmware
Risk mitigation: Quality assurance approach	➢ Minimizing internal short circuit risk through quality control over key cell manufacturing processes ➢ Scrutiny on LOPA (Layers of Protection Analysis) and PFD (Probability of Failure on Demand) to pinpoint risks and failure consequences at the design stage. ➢ Functional test and design review on ventilation systems	➢ Mitigate coolant leakage through leakage testing during system integration and FAT ➢ Functional tests on the alarming system during FAT under different operating scenarios	➢ Scrutiny on incoming quality control over key safety components, such as calibrated function tests on smoke sensors per UL 268. ➢ Functional test on emergency stop during FAT ➢ Function tests on FSS by triggering different levels of alarming ➢ Visual inspection FSS piping to identify risks that can lead to piping damage	➢ Water spray tests during FAT ➢ Functional test on isolation monitoring system

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Quality Data From 30+ GWh Track Record

Overview of Finding Distribution

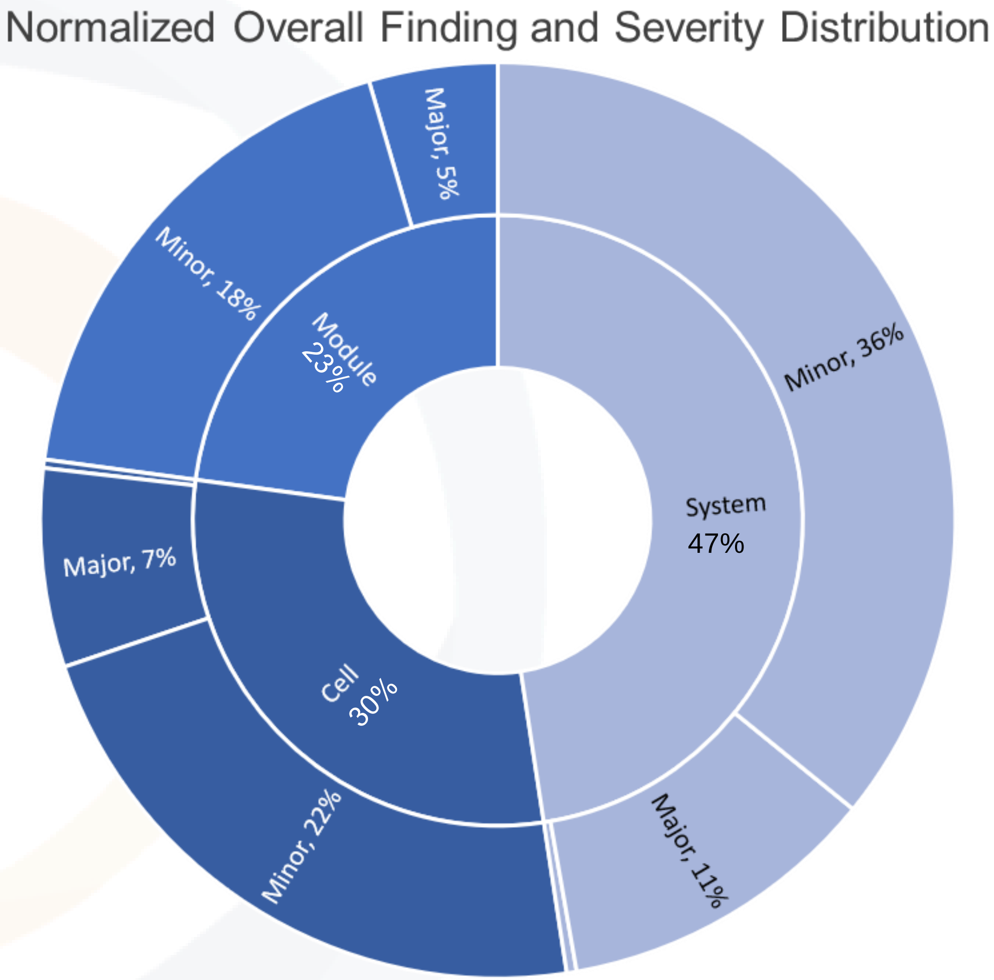
System-level findings contributed to nearly 50% of the total findings due to the highly manual integration processes and procedural complexity.

Module Manufacturing

- Module lines are less automated, which creates room for imprecision in material handling and inferior welding quality.

Cell Manufacturing

- Although battery cell factories have the highest level of automation, they tend to have larger number of findings, comparing with modules, due to its lengthy production processes.
- Audit findings on cell usually have higher severity rating, as cell is the building block of the ESS and cell defects can be detrimental to the system performance and safety.



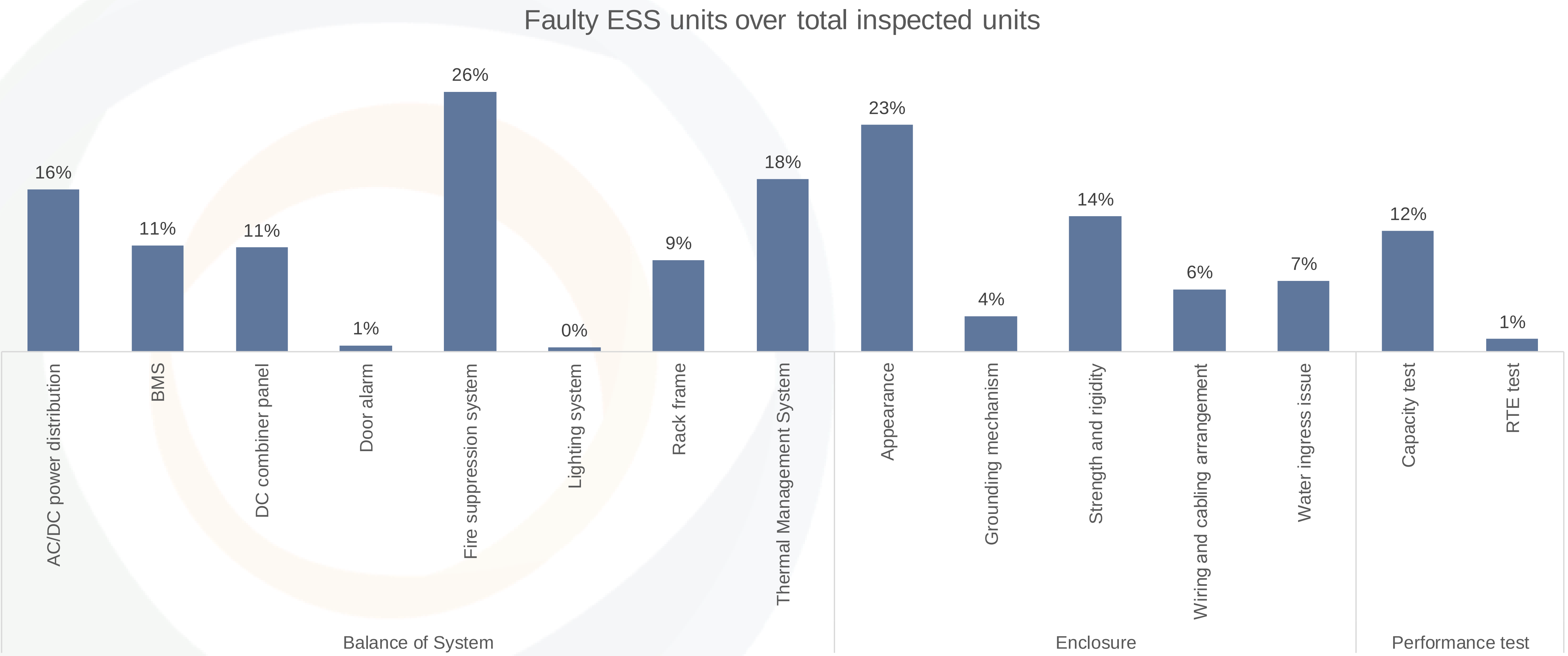
System Integration

The large number of system-level findings is mainly caused by the following two contributors:

- The highly manual integration process without stringent quality control procedures
- System's vulnerability to underlying problems originating from the upstream components

System-Level Finding Occurrence

Fire suppression system, enclosure appearance, and thermal management system are the most found malfunctioning components for any inspected ESS units.



System-Level Finding Distribution

BOS and enclosure defects contributed to most of the system-level findings. Performance test failure usually indicates deeper-rooted problems.

Enclosure

Enclosure related findings contributed to 34% of the total system-level findings. However, majority (84%) of the enclosure related findings are minor.

Enclosure finding examples:

- Appearance defects: painting specifications, markings, nameplate, openings, etc.
- Poor strength and rigidity: lifting provision test, structural deformation, etc.
- Poor wiring and cabling arrangement
- Grounding mechanism defects
- Water ingress issue

BOS (Balance of System)

BOS related findings contributed to 58% of the total system-level findings. The findings in BOS are typically caused by component defects and bad practices during system integration.

BOS finding examples:

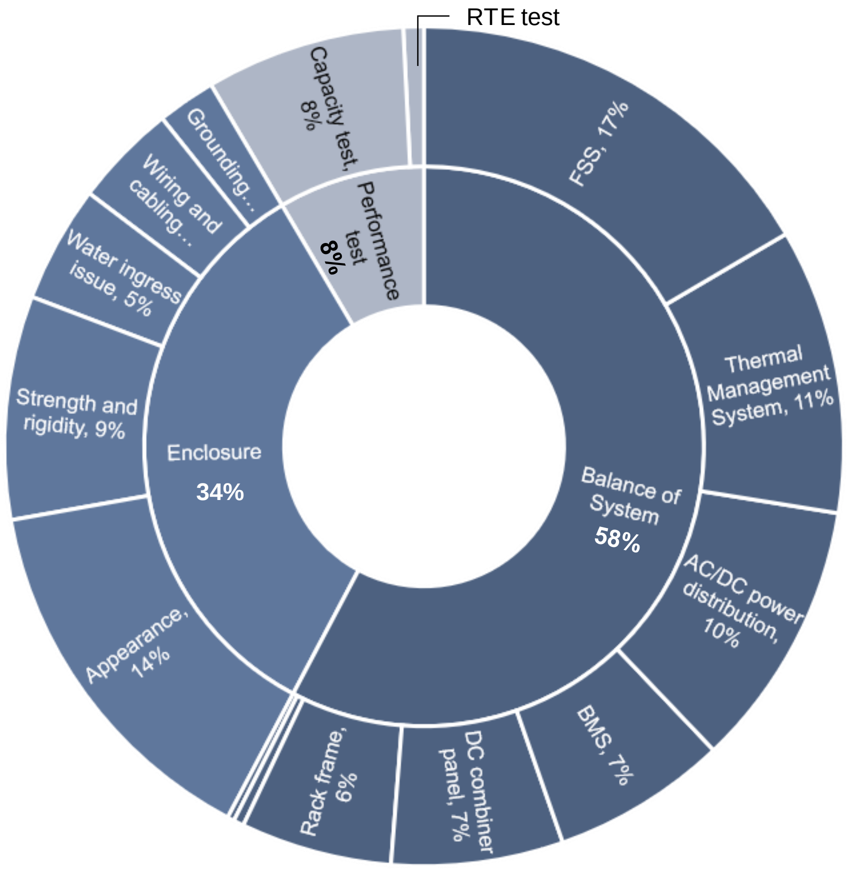
- Liquid coolant leakage due to deformed flange plates, defective valves, loose pipe connections within the coolant circulation system
- Malfunctioning temperature, smoke, gas sensors, audible and visual alarms due to internal mis-wiring
- Live conductor exposed within the AC/DC distribution

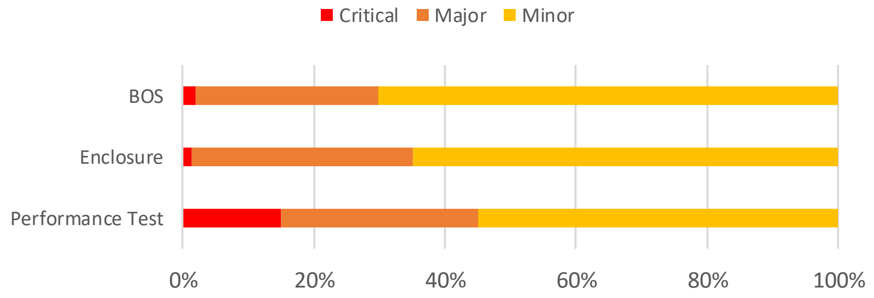
Performance Test

Performance test findings contributed to 8% of the total system-level findings.

Performance test finding examples:

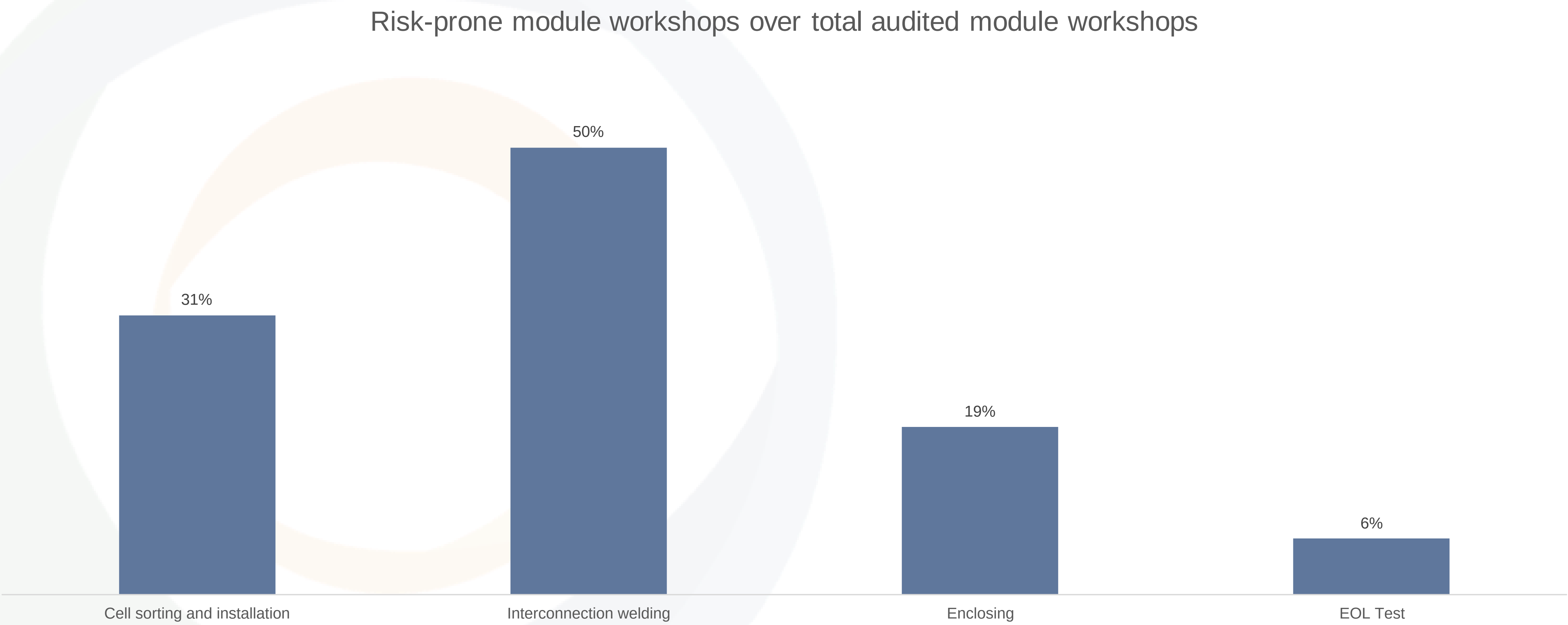
- Underachieving capacity and RTE results from abnormally large temperature and voltage variations among battery cells within a module, due to high impedance from poorly welded wiring connections
- Charging/discharging failure due to wiring issues in battery rack’s high voltage boxes





Module-Level Finding Occurrence

Interconnection welding, cell sorting, and cell installation are the most risk prone processes for any inspected module workshops.



Module-Level Finding Distribution

As module production's automation level varies among manufacturers, welding quality issues and environmental control pitfalls can lead to EOL (End-of-Line) test failures.

Cell Sorting & Installation

Cell installation covers the module assembly process prior to interconnection welding, including cell sorting, electrode cleaning, and fixing to the module set.

Cell sorting and installation finding examples:

- Cell installation: Lack of error-proofing measures to ensure cells are assembled with the right orientation, inconsistent glue usage and position, unqualified BOM (Bill of Materials) change on insulation layers within the module.

Interconnection Welding

Interconnection welding covers interconnection busbar welding, sensor welding, wiring, and static module tests (OCV, IR).

Interconnection welding finding examples:

- Interconnection welding: Mislocated welding position, non-calibrated welding strength test, lack of procedure of cleaning up welding slags

Enclosing

Enclosing covers cell group insertion, module coding, pole positioning and cleaning

Enclosing finding examples:

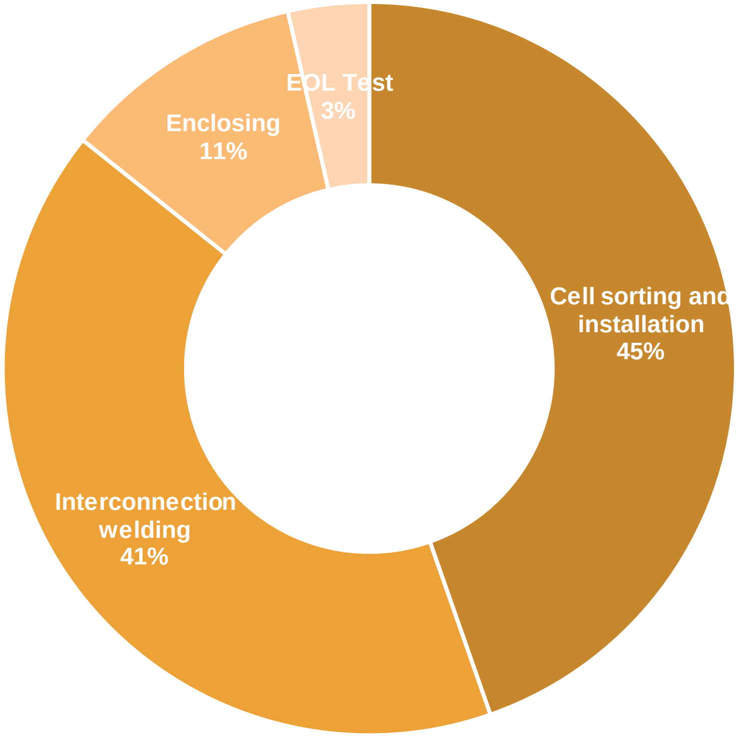
- Enclosing: Inconsistent barcode placement, poorly executed 5S

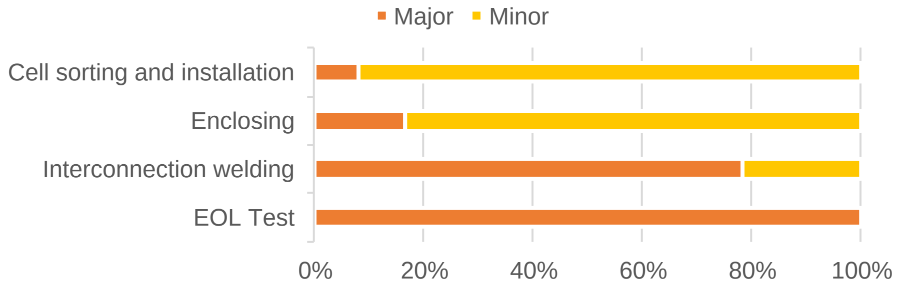
EOL Test

Static module tests including OCV, IR measurement and dielectric withstand voltage test.

EOL test finding examples:

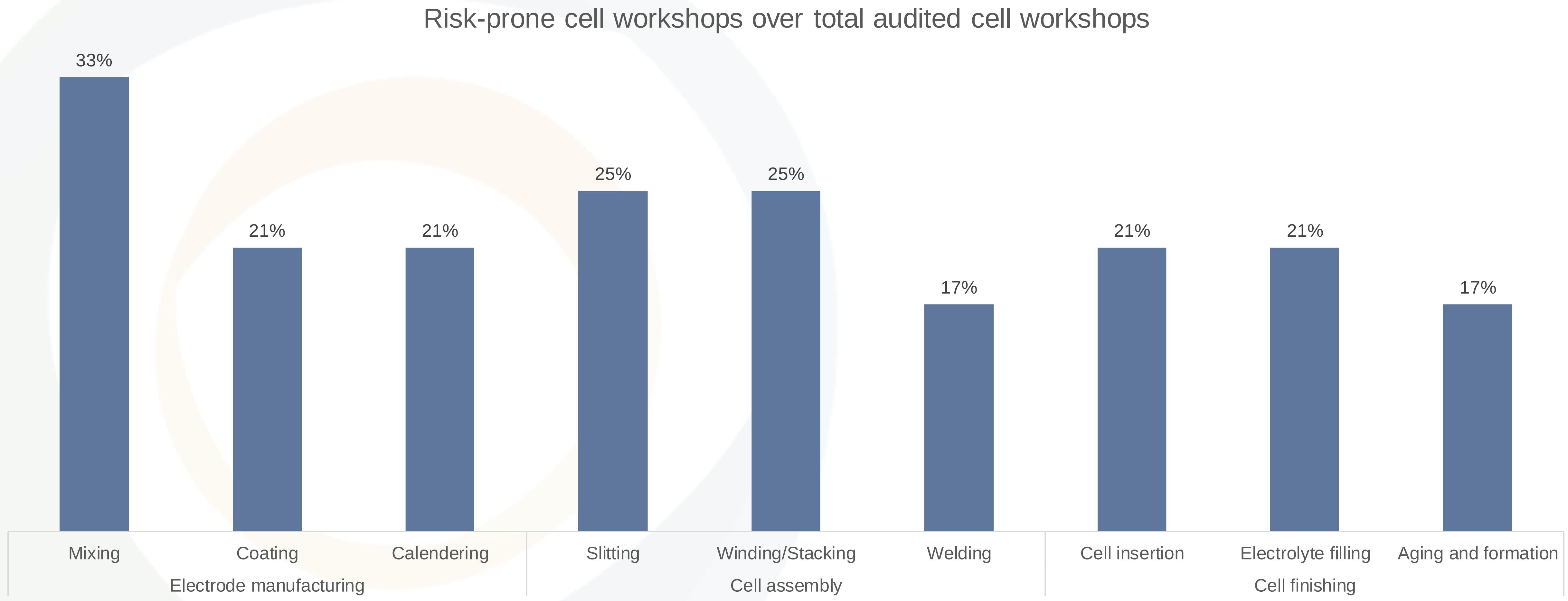
- EOL tests: Failed dielectric withstand voltage test due to poor internal wiring insulation and wiring arrangement, abnormal cell voltage difference due to defective cells





Cell-Level Finding Occurrence

Mixing, slitting, and winding/stacking are the most risk prone processes for any inspected cell workshops.



Cell-Level Finding Distribution

Evenly distributed number of findings indicates high precision and safety requirement throughout the cell manufacturing process.

Electrode Manufacturing

Electrode manufacturing includes mixing, coating, and calendaring processes.

Electrode manufacturing finding examples:

- Mixing: out-of-calibration viscosity meter, lack of expiration control record over the mixed active material
- Coating: missing key coating quality measurements such as surface density, coating thickness, and moisture content.
- Calendaring: deformed electrode sheets due to roller misalignment

Cell Assembly

Cell assembly covers slitting, stacking/winding, and tab welding.

More than 40% of the findings in the cell assembly process are rated major, due to their close affiliation with internal short circuit hazards.

Cell assembly finding examples:

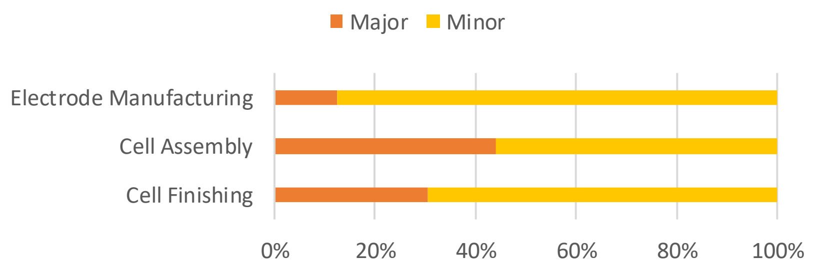
- Slitting: lack of burr size control, lack of monitoring on the cutter status and remaining life
- Stacking/winding: lack of inline electrode alignment inspection
- Welding: uncalibrated welding strength test that are conducted manually without well-defined pass/fail criteria

Cell Finishing

Cell finishing covers cell insertion, electrolyte filling, aging and formation.

Cell finishing finding examples:

- Cell (jelly-roll/stack) insertion: lack of laser welding parameter verification, lack of inline alignment and clearance inspection after the aluminum cap is welded on
- Electrolyte filling: Loose control of environmental conditions (temperature and humidity), lack of sealing quality inspection which can lead to electrolyte leakage



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Case Studies

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- *Fire Detection and Suppression System Failure*
- *Liquid Cooling System Failure*
- *Gaps in FAT Protocols*

Case Study – Fire Detection And Suppression System

Client	US and EU regions
Product type	Containerized BESS
Component	Fire detection and suppression system
Supplier	Tier 1 located in China
Project size	75 MWh in total
Project date	2021 to 2022
QA activity	Factory Acceptance Test
Findings	1. Non-responding release actuator for the fire extinguishing agent 2. Fire alarm sign didn't light up with a triggered alarm 3. Ventilation fans were installed backwards 4. Fire alarm abort button was not functional 5. Non-responding smoke and temperature sensors due to wiring mistakes 6. FSS pipe had no protective rubber sleeve

1. Fire extinguisher electric actuator

2. Fire alarm sign not lighting up

3. Hydrogen ventilation fan

4. Fire alarm abort button

5. Non-responding gas and heat sensors due to mis-wiring

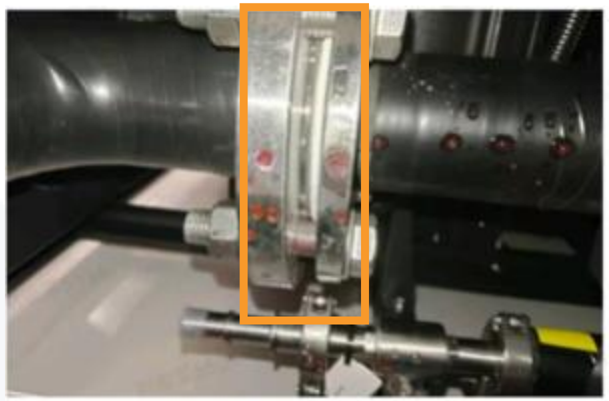
6. Missing rubber sleeve

Case Study – Fire Detection And Suppression System

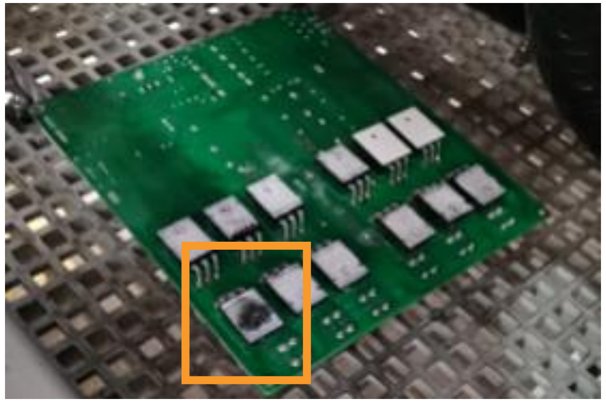
No.	Finding Description	Root Causes	Risk Analysis	Corrective Action
1	Non-responding release actuator for the fire extinguishing agent.	**Faulty diode** within the actuator	System's disability in stop **early-stage fire propagation**.	Faulty diode was replaced.
2	Fire alarm sign didn't light up with a triggered alarm.	**Faulty internal components**	Deficiency in **visual fire emergency notification**.	The complete fire alarm sign was replaced with a new one.
3	Reversely installed exhaust fans	**Mis-wiring**	Concentrated hydrocarbon gases that poses **fire and explosion risks.**	The ventilation system was correctly re-wired to allow efficient ventilation.
4	Fire alarm abort button was not functional	**Mis-wiring**	Unwanted fire extinguishing agent release or sprinkler system activation, which was one of the contributing factor that caused the thermal runaway incident for **"Moss Landing Phase I".**	The emergency abort button wiring was corrected.
5	Non-responding smoke and temperature sensors	**Mis-wiring**	System's disability in **detecting thermal runaway at early stage**.	Smoke and temperature sensors wiring were corrected.
6	Fire suppression system pipe had no protective rubber sleeve	**Operational error**	Direct metal-to-metal contact can cause friction leading to pipe damages that can result in fire extinguishing agent leakages onto the battery racks/modules. Given that the FSS pipe contains water, leakages onto battery racks may cause short circuiting that can lead to fire accidents. An example also comes from the **"Moss Landing Phase II"** where a leaking hose caused the suppression system to release water on battery racks.	Rubber sleeves were installed on pipes to prevent direct contact.

Case Study – Liquid Cooling System Failure

Client base	US
Product type	Containerized BESS
Component	Liquid cooling system
Supplier/Factory	Tier 1 located in China
Project size	>1 GWh
Project dates	2023
QA activity	Inline Production Monitoring (IPM)
Issues	• **Liquid cooling system leakage** from deformed flange plates, loose pipe connections, and defective valves. • **Unfunctional liquid circulation system** from internal short circuiting within key liquid coolant circulation components.



1. Leakage due to deformed flange plates



2. Compressor mainboard short circuiting

3. Loose pipe connection

4. Leakage due to a defective valve

Case Study – Liquid Cooling System Failure

No.	Finding Description	Root Causes	Risk Analysis	Corrective Action
1	**Deformed flange plates**	The flanges were deformed from overtightening due to a loosely defined screw mounting SOP (Standard Operating Procedure).	**Internal short circuiting** and **thermal runaway initiation** from continuous coolant leakage.	• Ring flanges were replaced and re-tested for leakage proof. • Screw mounting SOP was revised to avoid overtightening
2	**Compressor mainboard short circuiting**	Defective compressor mainboard	**Faster battery degradation** from unfunctional liquid cooling system.	• The mainboard was replaced • Incoming quality control procedures were tightened for the related compressor supplier.
3	**Loose pipe connections**	The fastener was not fastened from operator's mis-installation and not following SOP.	**Severe short-circuiting events** and **thermal runaway initiation** from potential massive coolant leakage.	• Reinforced operator training on the installation SOP. • An in-depth quality inspection on potential leakage-prone points was conducted.
4	**Defective three-way valve**	Defective incoming material: the valve comes with a loose stem.	**Faster battery degradation** from insufficient coolant flow control. **Internal short circuiting** and **thermal runaway initiation** from continuous coolant leakage.	• The defected valve was replaced • Incoming quality control procedures were tightened for the valves.

Case Study – Gaps in FAT Protocols

Client base	EU
Product type	Containerized ESS
Technology	Lithium-ion ESS
Supplier/Factory	Tier 1 and 2 suppliers, located in China
Project size	300 MWh
Project dates	2023
QA Activity	Contract review: Golden FAT
FAT protocol gaps	Electrical safety Functional safety System performance

Gaps in electrical safety test protocols

- Ground impedance test failed to cover all risk-prone components
- Dielectric withstand voltage test didn't cover all risk-prone circuits

Gaps in functional safety test protocols

- Missing BMS protective function test under abuse conditions: over/under voltage, over current, and high/low temperatures
- Missing tests on activation of all levels of fire alarms through heat, smoke, and gas sensors

Gaps in system performance test protocols

- Underrated RTE targets
- Missing pass/fail criteria on temperature and voltage deviations during cycling tests

Closing the Gaps: Golden FAT

- The ESS Golden FAT service includes both **document review** and **negotiation support**. System performance and safety risks are identified through the document review process. Based on the findings, negotiation support is provided to mitigate risks through imposing changes to improve the supplier's FAT protocols as outlined in contract exhibits.
- ESS Golden FAT helps with an early identification of risk posing deviations within supplier's checklists and minimize client's investment risks ensuring product stakeholders maximize the value of the system.

Golden FAT Methodology

ESS Golden FAT Checklist
- Incorporating prevailing UL, IEC, and NFPA standards and good practices from the industry

Checklist Review and Validation
- Validation of supplier's FAT checklist against the Golden standards.

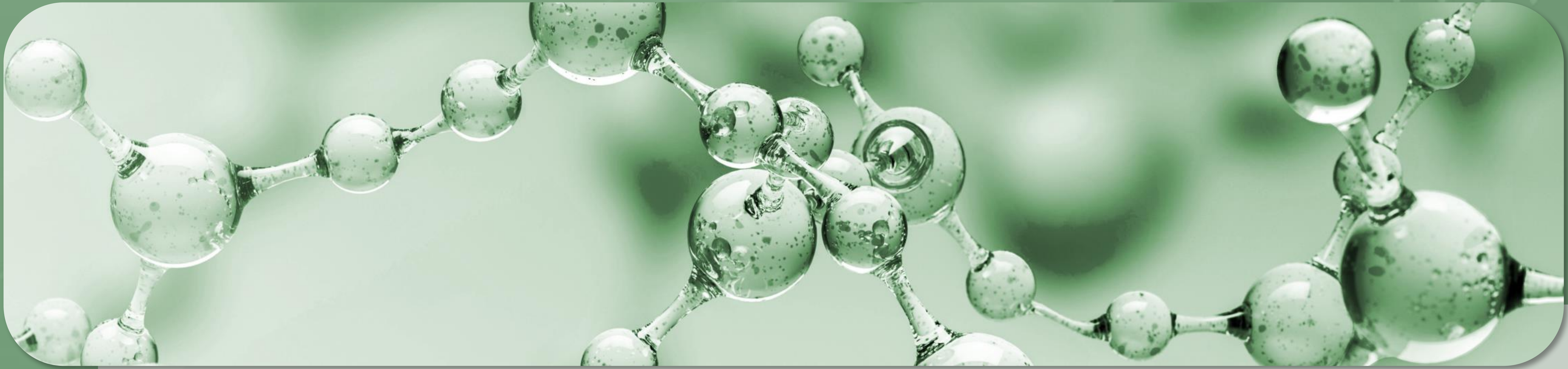
Negotiations and Adjustments
- Support client in negotiating and adjusting the FAT checklist deviations.

Documentation review
- Procurement contract review
- Project technical requirement review
- FAT checklist review

Negotiation support
- Support negotiating FAT terms with the supplier
- Draft FAT related Exhibits to be included in the Purchase Agreement

Key Takeaways

- There are no “perfect” battery, cell or system integration factories: CEA identified 1,300+ findings in 360+ inspections of 50+ factories.
- Quality assurance is the most efficient means to mitigate risks during mass production.
- System integration is the most risk-prone process due to its labor intensiveness, laxness in quality protocol execution, and difficulties in integrating all the different components.
- Gaps exist in supplier’s FAT practices. Quality assurance efforts should start early in the contract stage to minimize safety and performance risks.



Thank You

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