BATTERY ENERGY STORAGE SYSTEMS (BESS)

Fire Engineering & Electrical Engineering Design Basis

A Standards-Referenced Design Specification for Grid-Scale, Containerised Lithium-Ion Installations

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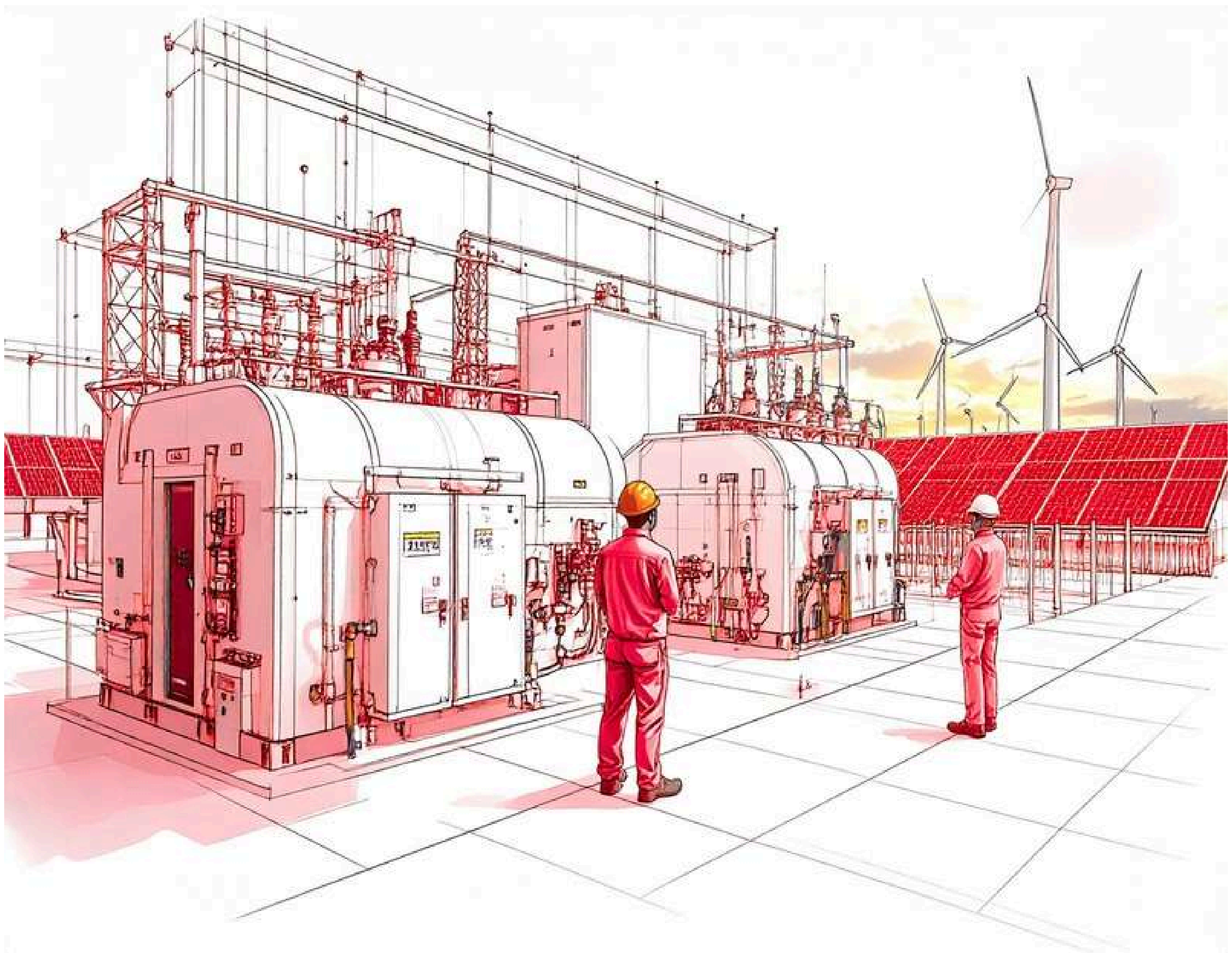
Introduction & Scope

1.1 Purpose and Applicability

This document establishes the fire engineering and electrical engineering design basis for grid-scale, containerised lithium-ion Battery Energy Storage System (BESS) installations, whether standalone, co-located with solar/wind generation, or deployed as part of Firm and Dispatchable Renewable Energy (FDRE) projects. It is written as a design specification for owners, developers, EPC contractors, and owner's engineers, and is intended to be invoked contractually at the FEED and detailed engineering stages.

The document integrates two disciplines that are too often engineered in isolation: the electrical system that creates and manages energy, and the fire safety system that must contain its uncontrolled release. Recent industry incidents — including power-conversion-system (PCS) fires originating in IGBT failures rather than in battery cells — demonstrate that a credible design basis must treat power electronics, cabling, and battery enclosures as distinct hazard sources, each with its own barrier set.

Applicability covers systems of aggregate energy above 600 kWh (the NFPA 855 threshold beyond which dedicated-use occupancy requirements apply), housed in ISO-container or purpose-built modular enclosures, deployed outdoors at ground level. Rooftop, indoor-occupied-building, and residential ESS are excluded, as are non-lithium chemistries (flow, sodium-sulphur), although the barrier methodology in Section 6 is chemistry-agnostic.



1.2 Definitions and Abbreviations

Term	Definition
BESS	Battery Energy Storage System — the complete installation including batteries, BMS, PCS, transformers, and auxiliaries
BMS	Battery Management System — the electronic system monitoring and protecting cells, modules,
PCS	Power Conversion System — bidirectional inverter converting DC battery power to grid-compliant AC
EMS	Energy Management System — supervisory control layer dispatching the BESS
Thermal runaway	Self-accelerating exothermic reaction within a cell releasing heat and flammable/toxic gas
Cascading / propagation	Spread of thermal runaway from an initiating cell to adjacent cells, modules, or units
Off-gas / vent gas	Gas mixture (H_2, CO, CO_2, electrolyte vapours, hydrocarbons) released during cell venting
Deflagration	Subsonic combustion of an accumulated flammable gas cloud within an enclosure
IGBT	Insulated-Gate Bipolar Transistor — the principal switching device within a PCS
SOC / SOH	State of Charge / State of Health
LFP / NMC	Lithium Iron Phosphate / Lithium Nickel Manganese Cobalt oxide cell chemistries
ESD	Emergency Shutdown
LOPA	Layer of Protection Analysis
SIF / SIL	Safety Instrumented Function / Safety Integrity Level per IEC 61508/61511
AHJ	Authority Having Jurisdiction (fire service, electrical inspectorate, CEIG in India)
FAT / SAT	Factory / Site Acceptance Test

1.3 Standards Hierarchy and Precedence

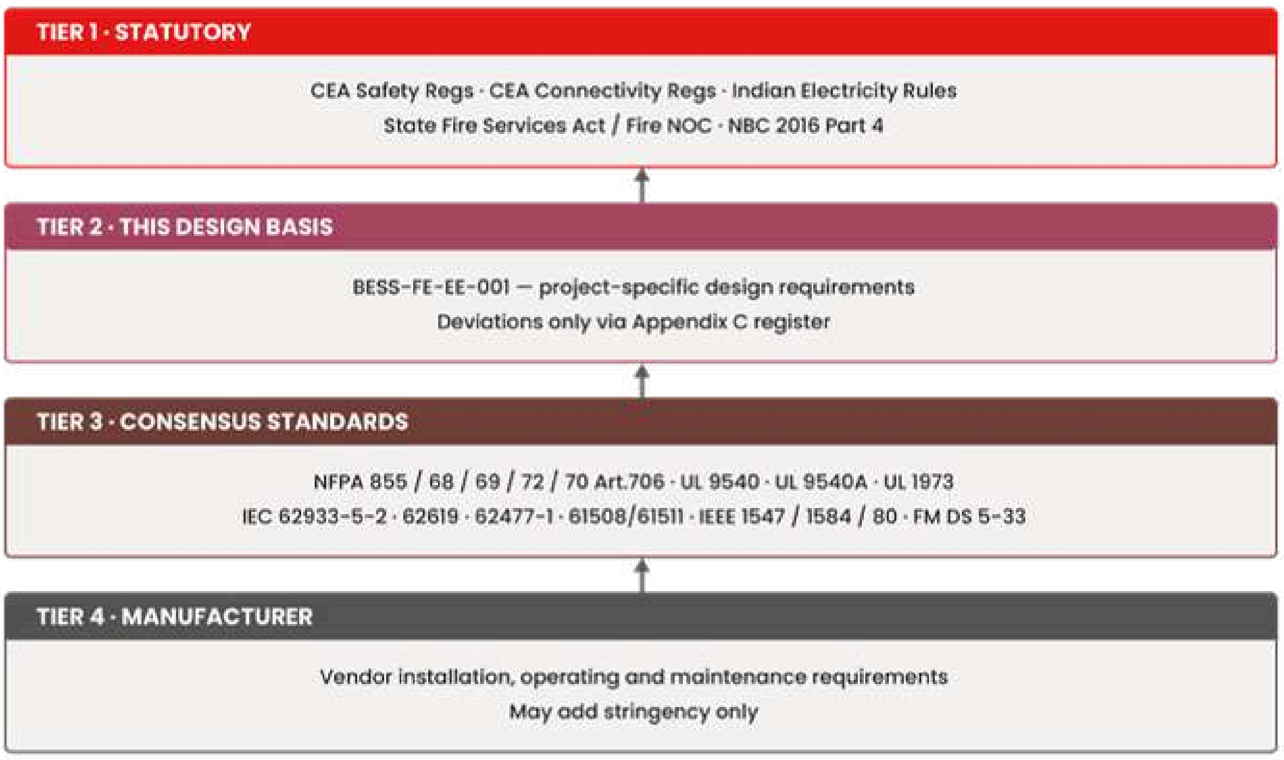
Where standards conflict, the following precedence applies: (1) statutory requirements of the jurisdiction (in India, the CEA Regulations, Indian Electricity Rules as amended, and State Fire Services Acts); (2) this design basis; (3) the referenced international consensus standards; (4) manufacturer requirements, which may only add stringency, never relax it. The project-specific deviations register (Appendix C) is the sole mechanism for departing from this document.

Standard	Title / Role in this Design Basis	Discipline
NFPA 855 (2026)	Standard for the Installation of Stationary Energy Storage Systems — governing installation standard: separation, size limits, protection requirements	Fire
UL 9540	Standard for Energy Storage Systems and Equipment — system-level product listing	Both
UL 9540A / EN 50604-2 pathway	Test Method for Evaluating Thermal Runaway Fire Propagation — data basis for spacing and ventilation design	Fire
IEC 62933-5-2	Electrical energy storage systems — safety requirements for grid-integrated EES systems (electrochemical)	Both
FM Global DS 5-33	Electrical Energy Storage Systems — insurer loss-prevention data sheet; most conservative spacing/sprinkler guidance	Fire
NFPA 68 / NFPA 69	Deflagration venting / Explosion prevention by ventilation and gas control	Fire
NFPA 72	National Fire Alarm and Signaling Code — detection and notification	Fire
NFPA 70 (NEC) Art. 706	Energy Storage Systems — electrical installation requirements	Electrical

IEC 62619	Safety requirements for secondary lithium cells and batteries for industrial applications	Electrical
UL 1973	Batteries for Use in Stationary and Motive Auxiliary Power Applications	Electrical
IEC 62477-1	Safety requirements for power electronic converter systems (PCS)	Electrical
UL 1741 / IEEE 1547	Inverter grid-interconnection safety and interconnection requirements	Electrical
IEC 61508 / IEC 61511	Functional safety of E/E/PE systems — SIL determination for safety instrumented functions	Both
IEEE 1584 / NFPA 70E	Arc-flash hazard calculation / electrical safety in the workplace	Electrical
IEC 60364 / IEEE 80	LV electrical installations / substation earthing	Electrical
IEC 60079 series	Explosive atmospheres — applied to off-gas accumulation zones where NFPA 69 route chosen	Both
CEA (Technical Stds. for Connectivity) & CEA Safety Regulations	Indian statutory grid-connection and electrical safety requirements	Electrical
IS 1646, IS 3034, NBC 2016 Part 4	Indian fire safety codes for electrical installations and buildings	Fire

Figure 1 — Standards Hierarchy and Order of Precedence

Where requirements conflict, the higher tier governs; lower tiers may add stringency, never relax it



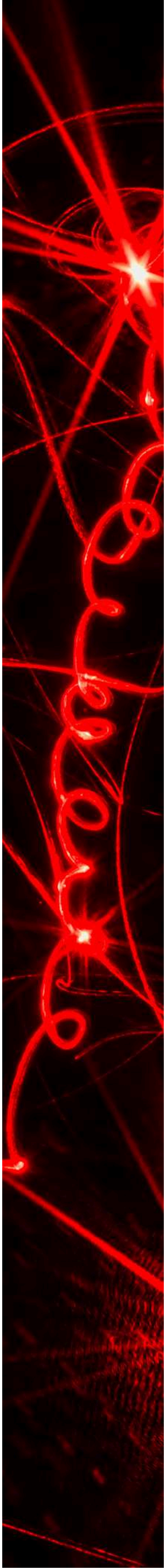
Hazard Characterization

2.1 Cell Chemistry and Thermal Runaway Mechanisms

Thermal runaway is the defining hazard of lithium-ion BESS. It initiates when a cell's internal temperature exceeds the stability threshold of its components — typically beginning with breakdown of the solid-electrolyte interphase around 80–120 °C, followed by separator collapse, internal short circuit, cathode decomposition, and electrolyte combustion. Once self-heating exceeds roughly 1 °C/min unabated, the reaction is autocatalytic and cannot be arrested by external cooling of the cell itself; the design objective shifts from prevention within the cell to containment of propagation beyond it.

Chemistry selection materially changes the hazard profile and shall be documented in the project hazard basis:

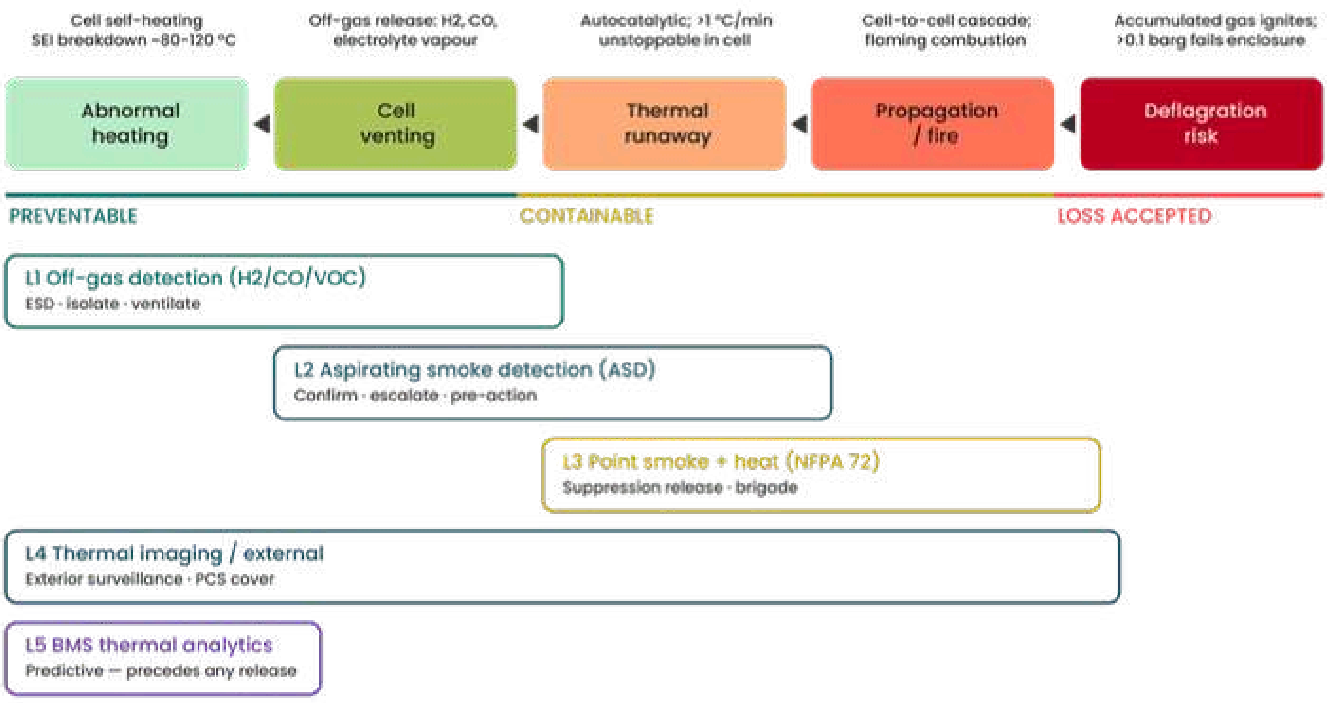
- **LFP ($LiFePO_4$):** higher onset temperature (typically 200 °C+), lower specific energy release, no oxygen liberation from the cathode. Propagation is slower but LFP off-gas is proportionally richer in hydrogen, shifting the dominant risk from fire toward deflagration of accumulated gas. Most Indian grid-scale procurement (including recent Rajasthan FDRE projects) is LFP.
- **NMC:** lower onset temperature (150–200 °C), higher energy density and heat release, cathode liberates oxygen sustaining combustion. Faster cell-to-cell propagation; fire is the dominant scenario.



Triggers shall be analysed across four classes: electrical abuse (overcharge, over-discharge, external short), thermal abuse (HVAC failure, external fire exposure, adjacent PCS fire), mechanical abuse (transport damage, crush, penetration), and internal defect (manufacturing contamination, lithium plating from low-temperature charging). Each class maps to a distinct barrier set in Section 6.

Figure 2 — Thermal Runaway Event Sequence vs. Detection & Intervention Windows

The earlier the detection layer, the more response options remain open



2.1 Cell Chemistry and Thermal Runaway Mechanisms

Cell venting precedes visible fire, often by minutes. Vent gas is a flammable, toxic mixture — typically 20–50% H_2 by volume, with CO, CO_2, CH_4, C_2H_4, and electrolyte solvent vapours (DMC, EMC, EC). Key design consequences:

- The mixture's lower flammability limit can be as low as ~6–10% in air, and hydrogen content gives it a very low minimum ignition energy and high laminar burning velocity — an accumulation ignited inside a closed container produces deflagration overpressures far exceeding container structural capacity (containers typically fail at < 0.1 barg; stoichiometric vent-gas deflagrations can exceed 4–6 barg unvented).
- A vented but unignited release creates an external flammable cloud; door-opening by responders is a recognised ignition/backdraft scenario (APS McMicken, 2019 — four firefighters injured by deflagration on entry).
- Toxicity (HF from fluorinated electrolyte decomposition, CO) governs responder PPE and site emergency planning, not only flammability.

The design shall therefore treat gas management as a discipline in its own right: detection of off-gas at the earliest (pre-thermal-runaway) stage, and either deflagration venting (NFPA 68) or exhaust ventilation preventing accumulation above 25% LFL (NFPA 69) — Section 5.2 sets the selection logic.

2.3 Failure Mode Taxonomy

A credible BESS fire risk model distinguishes originating equipment, because detection, suppression, and electrical protection differ for each. The taxonomy below shall structure the project HAZID:

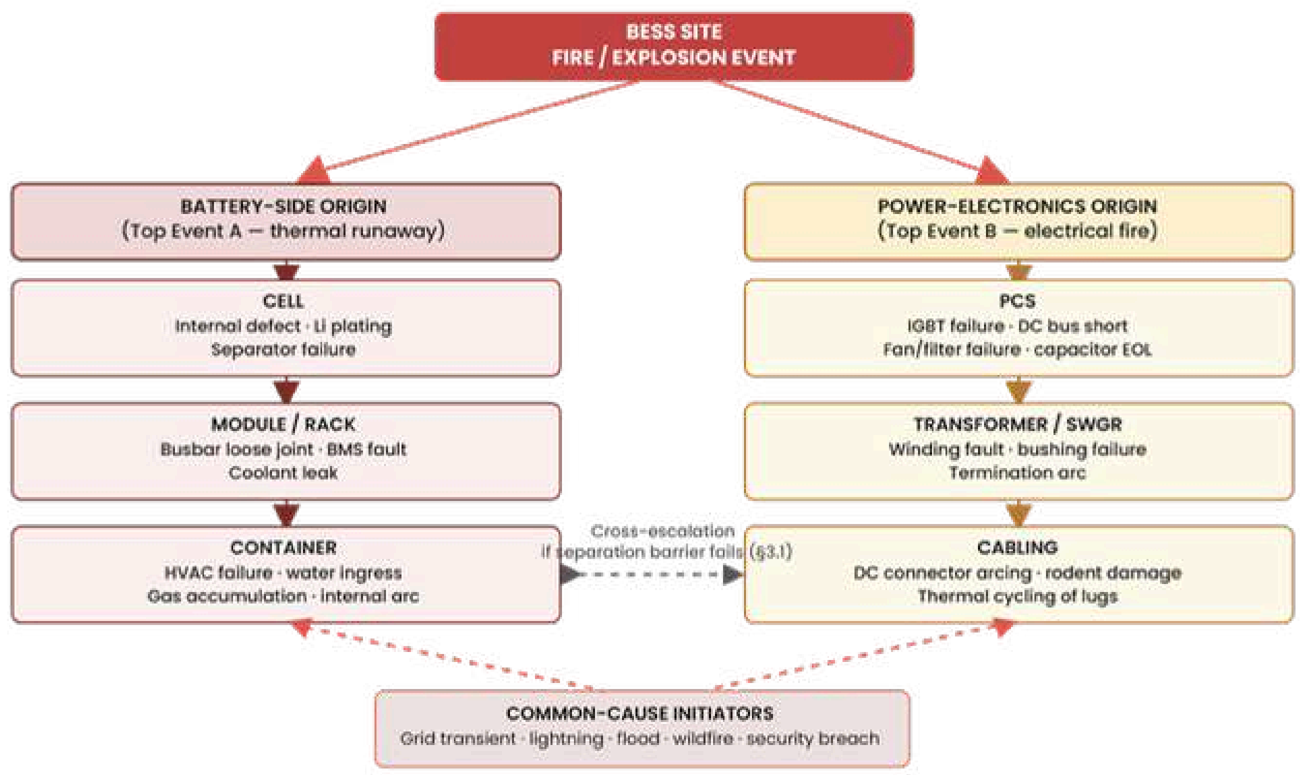
Level	Representative Failure Modes	Dominant Consequence	Primary Barriers
Cell	Internal defect, lithium plating, separator failure	Single-cell venting; possible module propagation	Cell quality (IEC 62619), BMS cell-level monitoring, inter-cell heat barriers
Module / Rack	Busbar loose joint, module BMS fault, coolant leak (liquid-cooled)	Multi-cell runaway, rack fire	Rack-level fusing, propagation-resistant design per UL 9540A rack test, in-rack detection
Container	HVAC failure, water ingress, internal arc, gas accumulation	Full-container fire or deflagration	Container thermal management, gas detection + ventilation/venting, compartment fire resistance
PCS / Power electronics	IGBT failure, DC bus short, cooling fan failure, capacitor degradation	Electronics fire; smoke damage; possible spread to adjacent units (ref. Pokhran, Jul 2026 — 4 PCS units, IGBT/short-circuit origin, containers undamaged)	DC/AC protection coordination, PCS internal detection, physical separation of PCS from battery enclosures

Transformer / switchgear	Winding fault, bushing failure, cable termination arc	Oil fire (if oil-filled), arc flash	Protection relaying, oil containment, fire walls per IEEE 979 / IS 1646
Cabling / connections	DC connector arcing, rodent damage, thermal cycling of lugs	Localised fire spreading along routes	Torque management + thermography, fire-rated segregation, FR-LSZH cable specification
Site / systemic	Grid transient, lightning, flood, wildfire exposure, security breach	Common-cause initiation of any above	Surge protection, earthing, site drainage, vegetation control, physical security

The distinction between battery-side and power-electronics-side events is not academic. A PCS fire is fundamentally an electrical-equipment fire — extinguishable, with well-understood detection — while battery thermal runaway is a chemical reaction that suppression can only cool and contain. Conflating them (as early media coverage of the Pokhran incident did, reporting container damage that had not occurred) leads to misdirected design spend and misinformed emergency response.

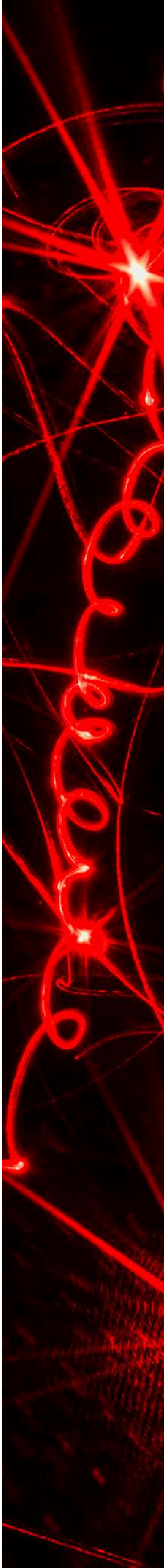
Figure 3 — BESS Failure Mode Taxonomy and Escalation Paths

Battery-side and power-electronics-side events are independent origins requiring separate barrier sets



2.4 Reference Incident Review

Incident	Year	Origin / Mechanism	Design Lessons Carried into this Document
APS McMicken, Arizona, USA	2019	Single-cell internal defect; runaway propagated through rack; unvented gas accumulation; deflagration on door opening injured responders	Off-gas detection ahead of smoke; NFPA 68/69 gas management mandatory; door-opening procedures and responder standoff in ERP; clean-agent-only suppression insufficient against propagation
Moss Landing (Vistra Phase I & subsequent events), California, USA	2021–2025	Indoor multi-MWh halls; water intrusion into heat-suppression system triggered event (2022); major 2025 fire in legacy indoor NMC hall	Outdoor modular architecture preferred over large indoor halls; water/suppression system MOC discipline; legacy-design retrofit risk; large-site smoke plume and community impact planning
Elkhorn / PG&E Monterey, USA	2022	Overheating event, sprinkler activation, no propagation beyond origin	Value of early detection + water application + unit segmentation; validated modular outdoor approach
ACME Pokhran, Rajasthan, India	2026	IGBT/short-circuit failure within PCS; four PCS units affected; no battery container involvement; in-house fire team controlled event; ~₹20 lakh revenue impact	PCS is an independent fire source demanding its own detection and separation; on-site first-response capability materially limits loss; disclosure and media-management plan needed because early external reporting overstated damage



Siting & Layout

Separation Distances

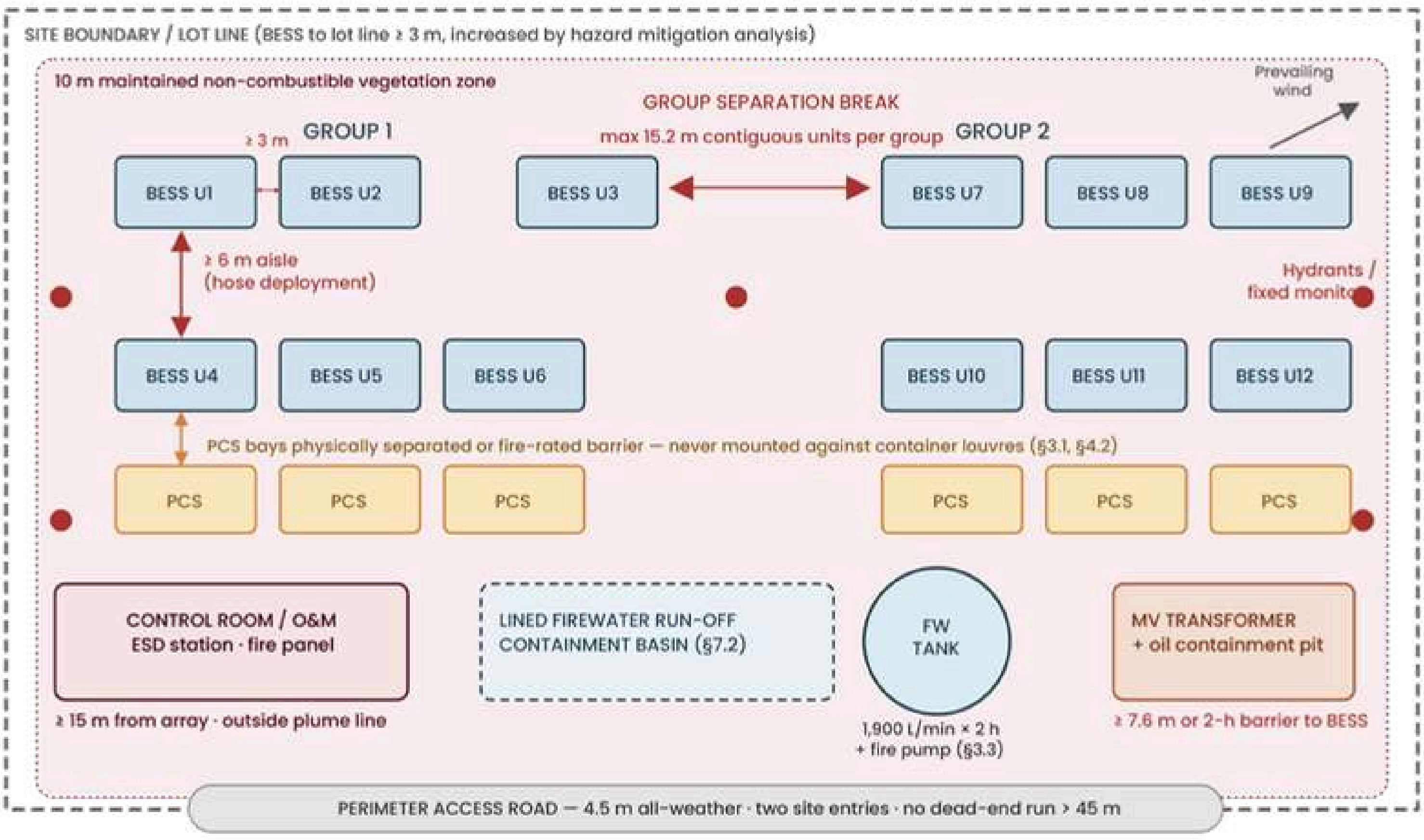
Layout is the cheapest and most reliable barrier in the entire design. Once a container is lost, separation — not suppression — is what prevents a single-unit event from becoming a site-loss event. The baseline requirements below follow NFPA 855 Chapter 9 (remote/outdoor installations) with FM Global DS 5-33 noted where more conservative; the stricter of the applicable values governs unless justified by test data per 3.2.

Exposure	Baseline Requirement	Notes
BESS unit to BESS unit	≥ 3 m (NFPA 855 default between units/groups); FM Global guidance favours ≥ 6 m or tested/engineered basis for large-format containers	Reducible only with UL 9540A installation-level data demonstrating no unit-to-unit propagation (see 3.2)
Group size limit	Maximum 50 ft (15.2 m) of contiguous units per group before a group separation break (NFPA 855 concept for outdoor arrays)	Arrange rows so any single group loss is financially and operationally tolerable
BESS to lot line / public way	≥ 3 m minimum, increased by hazard mitigation analysis; FM: consider 15 m to critical exposures	Plume/toxicity modelling may govern beyond radiant-heat spacing
BESS to PCS / inverter skid	Physical separation or fire-rated barrier; do not mount PCS on/against battery enclosure walls unless listed as a combined UL 9540 unit	Pokhran lesson: PCS fire must not radiate into container louvres/vents
BESS to transformer (oil-filled)	Per FM DS 5-4 / IEEE 979: ≥ 7.6 m or 2-h fire barrier; oil containment pit sized for full oil volume + firewater	Prefer ester-filled or dry-type at close range

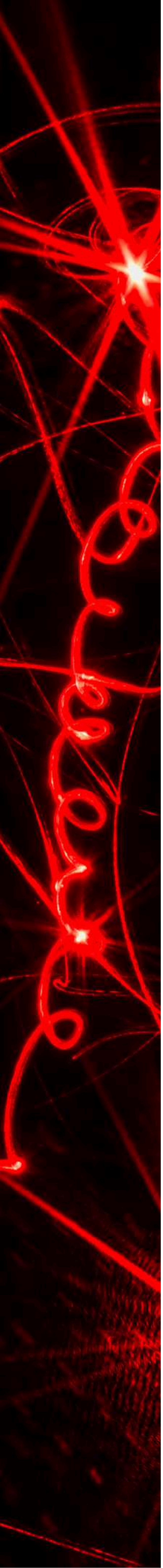
BESS to site buildings (control room, O&M)	≥ 15 m preferred; never within collapse/plume line of array	Control room houses ESD and must remain habitable during an event
BESS to switchyard / overhead lines	Outside falling-conductor envelope; ≥ 6 m from HV structures	Coordinate with electrical clearances (CEA Reg.)
Vegetation / wildland interface	10 m maintained non-combustible zone around array perimeter	Critical in Rajasthan/desert scrub sites; include in O&M contract

Figure 4 — Typical Array Layout and Separation Philosophy (Plan View, Not to Scale)

Separation is the primary barrier: once a unit is lost, spacing — not suppression — prevents a site-loss event



Prevailing wind orientation, plume line and single-contingency generation loss shall be assessed on this same drawing (§3.4)

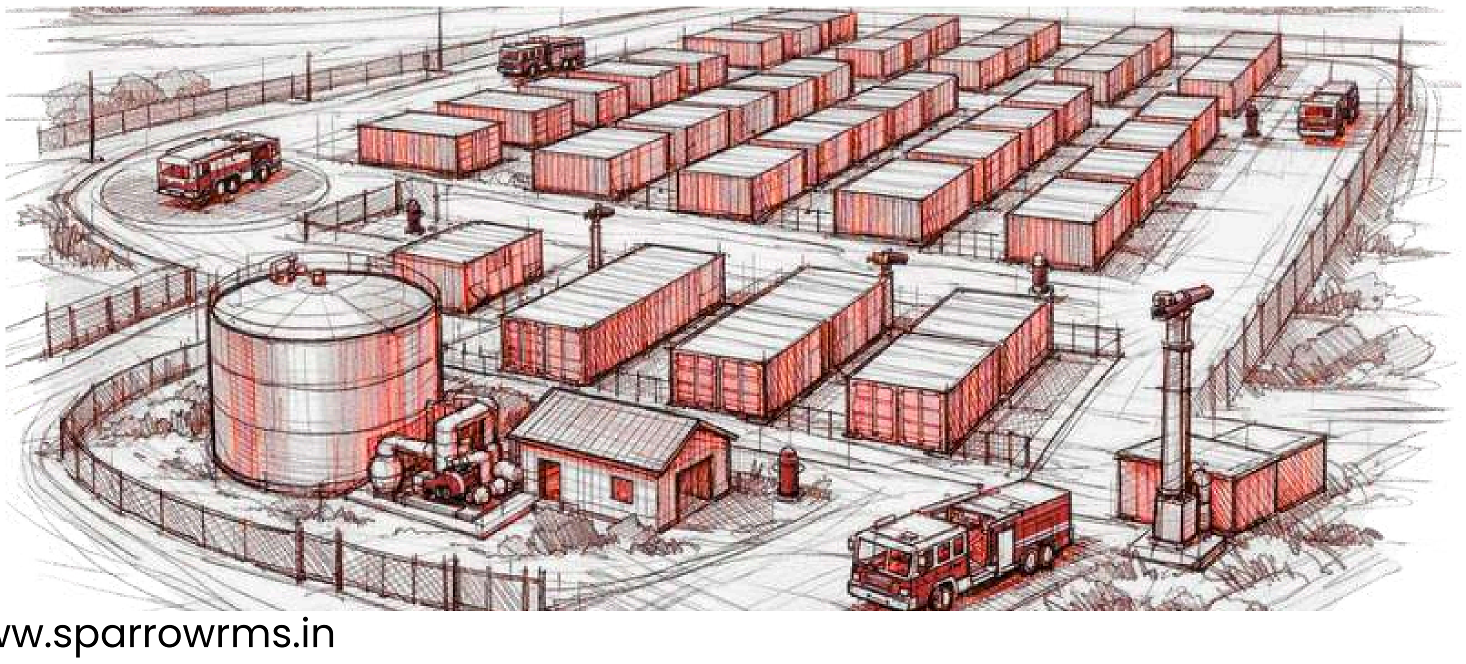


3.2 UL 9540A Test Data as Basis for Engineered Spacing

UL 9540A is not a pass/fail certification; it is a test method producing data at cell, module, unit, and installation level: gas volume and composition, heat release rate, flame extension, external surface temperatures, and whether runaway propagates between initiating and target units. A reduced-spacing or increased-group-size proposal shall only be accepted when: (a) the test report covers the same cell, module, rack and enclosure configuration as supplied (not merely the same cell model in a different enclosure); (b) installation-level testing demonstrates no propagation to target units at the proposed spacing with the proposed fire protection in operation; and (c) the AHJ and insurer have accepted the hazard mitigation analysis in writing. The owner's engineer shall verify test-report configuration equivalence during vendor evaluation — configuration drift between tested and supplied product is a recurring industry gap.

3.3 Fire Brigade Access, Egress and Water Supply

- Perimeter access road minimum 4.5 m width, all-weather, supporting fire appliance axle loads, with two independent site entry points and turning provision; no dead-end runs exceeding 45 m without turnaround.
- Every container face accessible within 45 m of an apparatus position; array internal aisles sized for hose deployment (≥ 6 m recommended between opposing rows where hose attack is part of the strategy).
- Water supply sized for exposure protection and cooling, not extinguishment of a battery in runaway: minimum 1,900 L/min for 2 hours available at the array (NFPA 855 hazard-analysis basis; FM guidance may drive higher). In water-scarce desert sites, provide dedicated storage with fire pump per NFPA 20/22 or IS equivalents, and document the basis in the ERP.
- Hydrant/monitor layout enabling cooling of adjacent (target) units without approach within the hazard standoff of the involved unit; consider fixed monitors for arrays where responder approach is undesirable.



3.4 Exposure to Adjacent Solar / Switchyard Assets

For co-located FDRE sites, the BESS array shall be laid out so that a full-container fire cannot damage the revenue-critical evacuation path (main transformer, pooling substation, transmission bay). Locate arrays downwind-preferred relative to control buildings using site wind-rose data, maintain PV string inverters and DC combiner routing outside the BESS plume line, and ensure a container event cannot trip more generation than the grid connection agreement tolerates for single-contingency loss. The financial-risk layout review shall be documented alongside the fire layout review — they are the same drawing.

Electrical Engineering Design

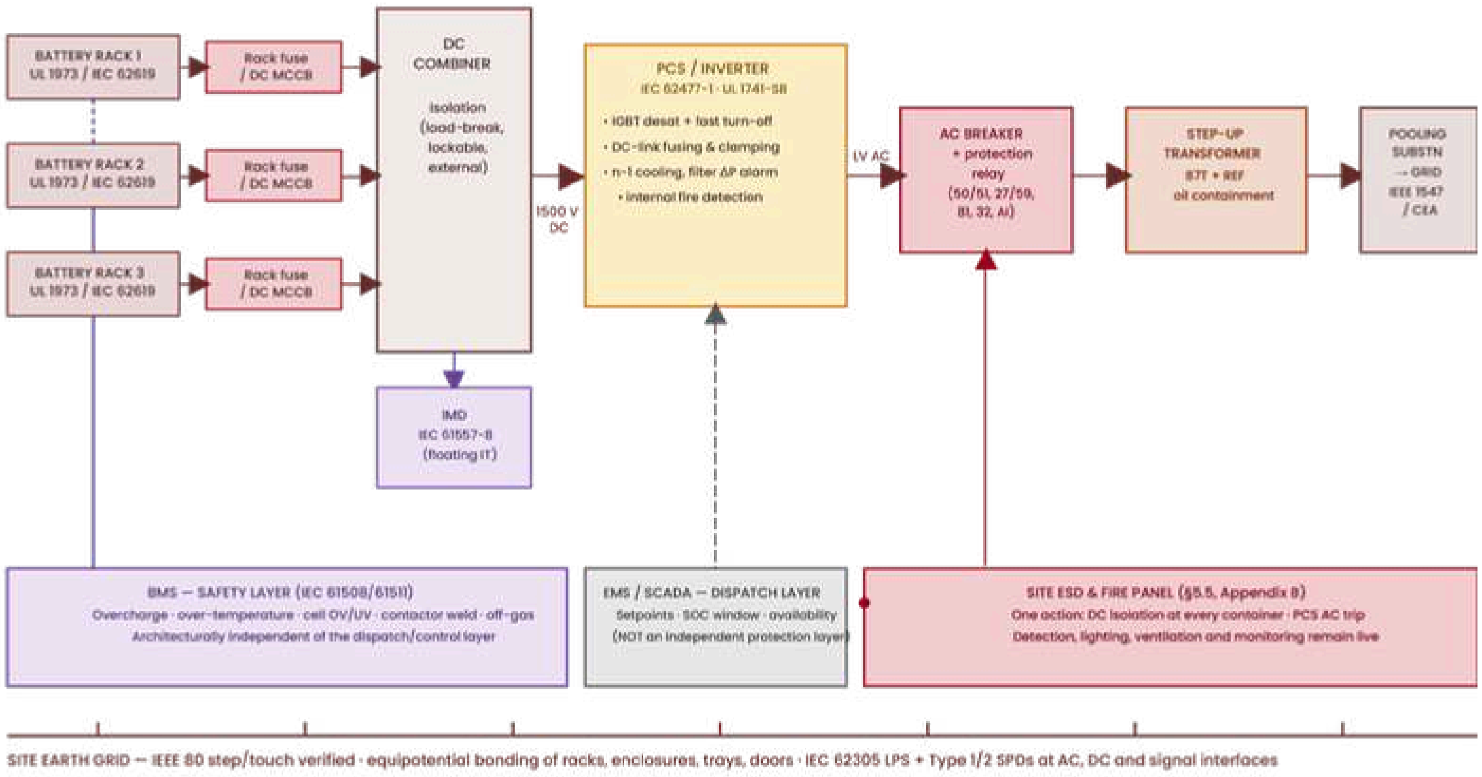
4.1 DC Architecture — String Sizing, Fusing and Isolation

The DC side of a BESS is a stiff, high-fault-energy source that cannot be de-energised at its origin: the cells remain charged regardless of switch state. The architecture shall therefore be built on segmentation and selective isolation.

- Battery and rack construction to UL 1973 / IEC 62619; system voltage typically 1,000–1,500 V DC. All equipment on the DC bus rated for maximum charge voltage plus regulation tolerance, at site maximum ambient (55 °C design ambient for Rajasthan-class desert sites).
- Each rack protected by a rack-level fuse or DC breaker sized for cell manufacturer short-circuit contribution, with published DC fault current data verified at FAT — prospective fault current at the DC combiner routinely exceeds 50 kA on large containers.
- Load-break DC disconnects at rack and container level, lockable, accessible without entering the container (external isolation point), interlocked with the ESD scheme (5.5). Selectivity study covering fuse–fuse and fuse–breaker coordination across rack, combiner and PCS input levels.
- Pre-charge circuits on all contactor closures to prevent inrush welding; contactor weld detection implemented in BMS with alarm to EMS.
- DC cabling: flexible Cu, 90 °C insulation minimum, FR-LSZH sheath, sized for 1.25× continuous current with derating for grouped tray routing at design ambient; connectors of a single manufacturer system (no cross-mated MC4-type mixing — a known fire initiator in PV practice equally applicable here).

Figure 5 — Representative Single Line Diagram with Protection and Isolation Architecture

DC side is a stiff source that cannot be de-energised at origin — architecture is built on segmentation and selective isolation



Relay coordination study shall bracket minimum and maximum credible fault contribution across SOC range, PCS current-limit mode and number of units online (§4.4)
Arc-flash study per IEEE 1584 (AC) and NFPA 70E Annex D methods (DC); remote switching where incident energy exceeds 8 cal/cm² (§4.2)

4.2 PCS / Inverter Design — IGBT Protection, Short-Circuit Coordination, Arc Flash

The PCS is a fire source in its own right, as the Pokhran incident demonstrated. Its protection philosophy shall address both grid-side and battery-side contributions, and the failure of its own switching devices.

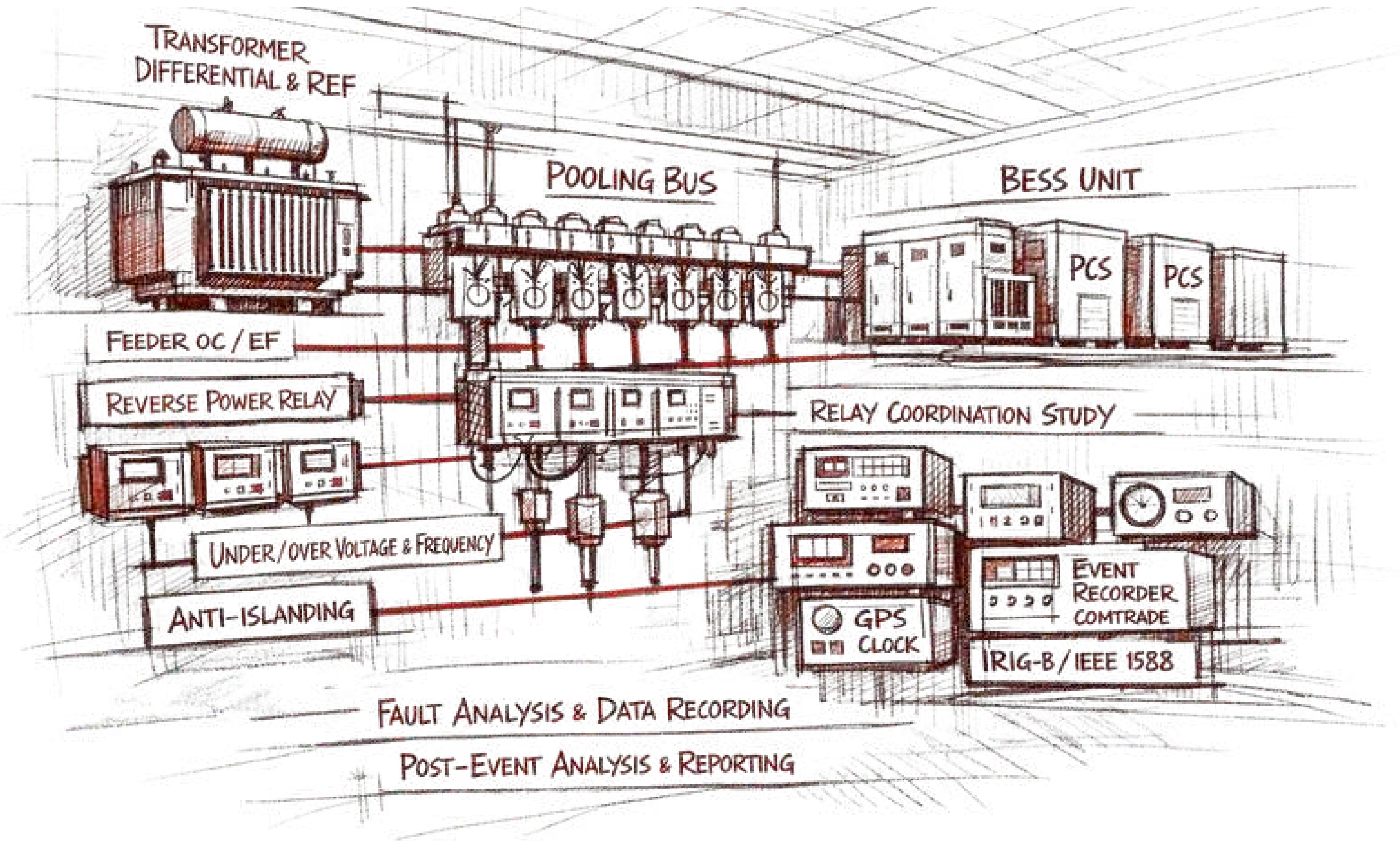
- PCS designed and certified to IEC 62477-1 (safety of power electronic converters) and, for grid interface, UL 1741-SB / IEEE 1547-2018 with applicable Indian CEA connectivity amendments.
- IGBT protection: desaturation detection and gate-driver fast turn-off (< 10 µs), DC-link overvoltage clamping, dv/dt and di/dt limits per device datasheet, and thermal modelling per IGBT junction with derating verified at 55 °C ambient with one cooling fan failed (n-1 cooling).
- Internal DC bus fusing rated to interrupt combined battery + DC-link capacitor discharge; capacitors specified with fail-safe (open, non-rupture) end-of-life mode and pressure-relief construction; capacitor bank compartmentalised from control electronics.
- Cooling: filtered forced air or liquid; fan failure alarmed and auto-derating implemented; dust management plan for desert deployment (filter DP monitoring — clogged filters are a leading PCS overheating cause).
- Arc-flash study per IEEE 1584 for every AC bus and per DC methodologies (e.g., Stokes/Oppenlander per NFPA 70E Annex D) for DC combiner and PCS input sections; incident-energy labels fitted; remote racking/switching provided wherever calculated energy exceeds 8 cal/cm².
- PCS enclosures separated from battery enclosures per 3.1; PCS internal fire detection per 5.1 with trip-and-alarm to EMS and site fire panel.

4.3 Earthing, Bonding and Insulation Monitoring

- Site earth grid designed per IEEE 80 (step/touch verified by CDEGS or equivalent), integrated with the pooling substation grid; soil-resistivity survey mandatory — desert soils are high-resistivity and typically require enhanced electrode design.
- DC system earthing philosophy declared and consistent: floating (IT) DC with continuous insulation monitoring device (IMD) per IEC 61557-8 is the default for 1,500 V systems; first-earth-fault alarm, second-fault trip logic documented.
- Equipotential bonding of racks, enclosures, trays and doors; bonding jumpers across hinged panels; lightning protection per IEC 62305 risk assessment, with SPDs Type 1/2 coordinated at AC and DC interfaces and on all signal/communication lines entering containers.

4.4 Protection Relaying and Grid Interface

- Protection scheme covering: transformer differential and REF, feeder overcurrent/earth-fault, directional elements for reverse-power scenarios, under/over-voltage and frequency per IEEE 1547 and CEA connectivity standards, anti-islanding, and breaker-failure backup at the pooling bus.
- Relay coordination study covering the full charge and discharge fault-contribution range — BESS fault current varies with SOC, PCS current-limit mode, and number of units online; the study shall bracket minimum and maximum credible contributions.
- Metering, event recorders (COMTRADE), and time synchronisation (IEEE 1588/IRIG-B) to enable post-event root-cause reconstruction — the electrical analogue of the black box, and essential for insurance and regulatory reporting.



4.5 BMS Functional Safety — SIL Assessment

The BMS is not merely a monitoring device; specific BMS actions are safety instrumented functions and shall be treated as such under IEC 61508/61511:

Candidate SIF	Initiating Cause	Safe State Action	Typical Target
Overcharge protection	PCS control failure, EMS setpoint error	Open rack/container contactors; inhibit charge	SIL 2 (LOPA to confirm)
Over-temperature trip	HVAC failure, module hot-spot	Isolate affected rack; escalate to container trip	SIL 1–2
Cell overvoltage/undervoltage	Cell imbalance, sensing fault	Isolate string; alarm	SIL 1–2
Off-gas detected → ESD	Cell venting	Trip container, initiate ventilation/suppression sequence per 5.5	SIL 2
Contactor weld response	Contactor failure	Open redundant isolation device; alarm	SIL 1

Requirements: independence of the safety layer from the control (dispatch) layer; hardware fault tolerance and proof-test intervals derived from SIL verification calculations; BMS firmware under management-of-change control with vendor security patching obligations (IEC 62443 alignment for OT cybersecurity); and end-to-end trip testing at SAT, not merely simulation at FAT.

4.6 Cabling, Segregation and Fire-Rated Routing

- Power, control, and safety-system cabling segregated on separate trays or by barriers; safety circuits (detection, ESD, fire panel) in fire-resistant cable to IEC 60331 / IS 17505 circuit-integrity ratings where they must operate during a fire.
- Tray penetrations through fire barriers sealed with tested firestop systems; cable routes avoid passage over or against battery container vent/deflagration panels.
- Terminal torque management: torque-marked lugs, initial thermographic survey at commissioning under ≥ 80% load, then per the 8.2 predictive maintenance regime — loose DC terminations are among the most frequent BESS fire initiators worldwide.

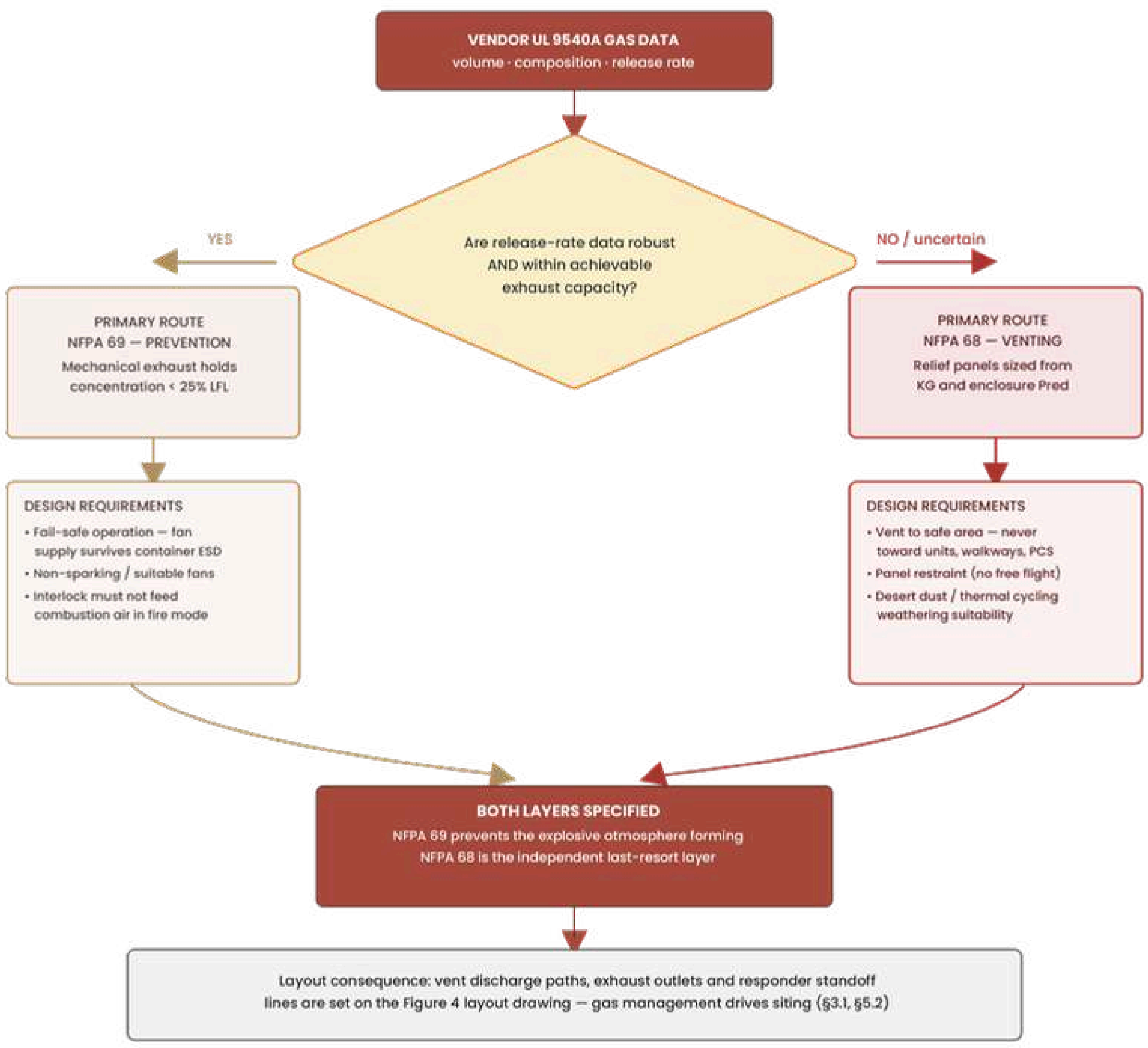
Fire Engineering Design

5.1 Detection Philosophy and Technology Selection

Detection design follows the physics of the event sequence: gas before smoke, smoke before heat, heat before flame. The earlier the detection layer, the more options remain open — a confirmed off-gas alarm minutes before runaway allows electrical isolation and ventilation while the event is still preventable; a heat alarm arrives when it no longer is.

Figure 6 — Gas Management Design Route Selection (NFPA 69 vs NFPA 68)

Specifying both is the default position of this design basis; omitting either requires a quantified deviation



Layer	Technology	Detects	Role
1 — Earliest	Off-gas sensors (H_2, CO, VOC electrochemical/ semiconductor), per container with cross-zoned voting	Cell venting precursor gases at ppm levels, pre-runaway	Initiate ESD, exhaust ventilation, operator alert — the prevention layer
2 — Early	Aspirating smoke detection (ASD/VESDA class) sampling rack aisles and exhaust plenum	Sub-visible smoke particles	Confirm event; escalate; pre-action for suppression release
3 — Confirmatory	Point smoke + heat (fixed temp / rate-of-rise) per NFPA 72	Established smoke/heat	Suppression release logic (cross-zoned with layer 2); fire brigade notification
4 — External / PCS	Thermal imaging cameras on array and PCS bays; PCS internal smoke detection; linear heat detection on cable routes	Hot spots, electronics fires, cable fires	Covers non-battery fire sources (ref. Pokhran); early exterior surveillance
5 — Systemic	BMS thermal analytics (cell delta-T trending, self-heating rate alarms)	Electrical/thermal precursors before any release	Predictive layer; feeds 8.2 maintenance triggers

•All detection signals to an addressable fire alarm panel per NFPA 72 / IS 2189, with EMS/SCADA integration for remote annunciation to the 24×7 monitoring centre; no BESS site shall rely on locally-annunciated-only alarms.

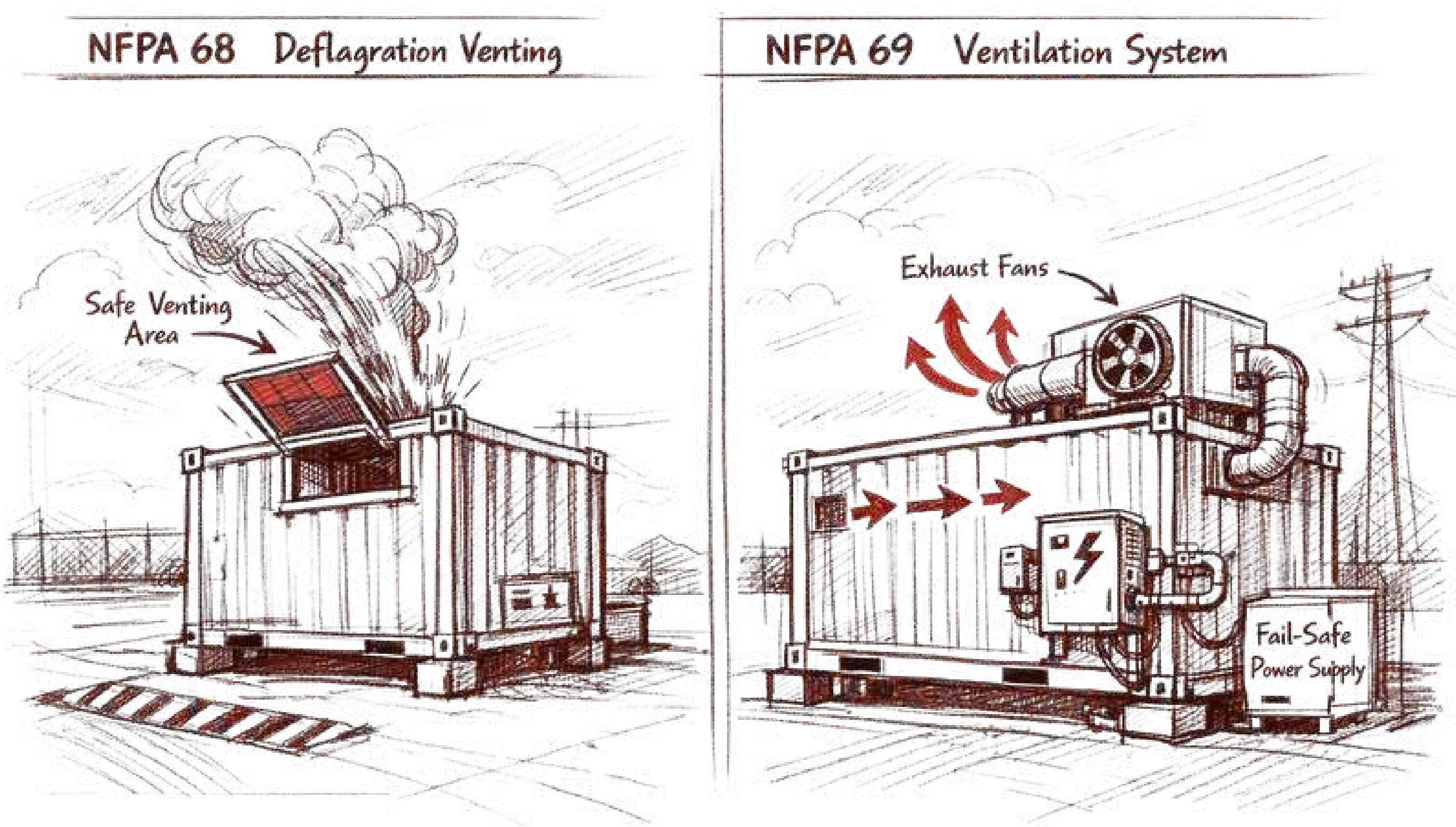
•Voting logic documented: single off-gas detector = alert + investigate; two detectors or gas + ASD = ESD sequence per 5.5. Spurious-trip economics shall not be allowed to erode the single-detector alert function.

5.2 Explosion Prevention and Venting — the NFPA 68 vs NFPA 69 Decision

Every containerised lithium-ion enclosure shall have an engineered gas-management basis. Two compliant routes exist and the selection shall be explicit, documented, and supported by vendor UL 9540A gas data (volume, composition, release rate):

- **NFPA 68 —** Deflagration venting: relief panels sized from the vent-gas deflagration index (KG) and enclosure strength (Pred), opening at low overpressure to discharge the deflagration safely. Panels must vent to a safe external area (no discharge toward adjacent units, walkways, or PCS), and their existence changes the separation and access layout. Verify panel restraint (no free-flying panels) and weathering suitability for desert dust/thermal cycling.
- **NFPA 69 —** Prevention by ventilation: mechanical exhaust maintaining gas concentration below 25% of LFL for the design release rate, with fail-safe operation (ventilation must run during the event — powered from a supply that survives container ESD), certified non-sparking/suitable-for-atmosphere fans, and interlock logic that does not create a combustion air path once fire (as opposed to gas release) is confirmed.

Selection logic: NFPA 69 ventilation is preferred as the primary basis where vendor gas-release data are robust and release rates are within achievable exhaust capacity, because it prevents the explosive atmosphere from ever forming; NFPA 68 venting is then applied as the independent last-resort layer. Specifying both is the default position of this document and of insurer guidance (FM DS 5-33); omitting either requires a documented deviation with quantitative justification.



5.3 Suppression Philosophy — What Each Agent Does and Does Not Do

Agent / System	Effective Against	Limitations for Li-ion	Position in this Design Basis
Water (sprinkler / deluge / monitor)	Cooling adjacent cells and target units; controlling secondary combustibles; the only agent that removes meaningful heat	Does not stop runaway in the involved cell; run-off management needed; density matters (FM guidance trending ≥ 12.2 L/min/m² for in-container sprinklers)	Mandatory in some form: in-container sprinklers where architecture allows, plus external hydrant/monitor cooling capability sitewide
Clean agent (Novec-successors, inert gas)	Incipient electrical/electronics fires in sealed volumes; PCS and control cabinets	No bulk cooling — cannot stop or meaningfully delay propagation; agent lost when panels vent or doors open	Appropriate for PCS enclosures and control/electronics compartments; NOT accepted as sole battery-compartment protection
Aerosol (condensed)	Small enclosed electrical fires	Same cooling deficiency; visibility/clean-up issues	Acceptable inside module/rack micro-environments where vendor-listed; supplementary only
Water mist	Cooling with reduced water quantity; electronics-compatible	Performance highly design-specific; requires listed system with test evidence on comparable BESS	Acceptable alternative to sprinklers with UL 9540A-supported evidence
No internal suppression (containment strategy)	—	Accepts full loss of unit; relies wholly on spacing + gas management + external cooling	Only with installation-level UL 9540A non-propagation evidence, insurer concurrence, and AHJ acceptance in writing

The doctrinal position of this document: suppression protects the neighbours, not the patient. Design reviews shall reject any vendor claim that an internal agent 'extinguishes' thermal runaway; the honest engineering claims are delay, cooling, and prevention of secondary ignition — all valuable, none a substitute for separation and gas management.

5.4 Container Fire Resistance & Compartmentation

- Enclosure construction non-combustible; internal linings and cable trays low-flame-spread; battery compartment separated from LV/control compartment by a fire-resisting partition (minimum EI 60 recommended) so detection, BMS and isolation functions survive the early phase of a battery-compartment event.
- External wall fire performance selected against the radiant exposure of the design unit fire at the adopted spacing (UL 9540A external surface temperature data as input); where spacing has been reduced on test evidence, wall ratings compensate accordingly.
- Openings (HVAC louvres, cable entries, vent panels) positioned so they do not face adjacent units' openings; firestopped penetrations; door hardware openable from inside, and external door-status monitoring to the panel (doors ajar defeat both gas management and suppression).

5.5 Emergency Stop, ESD Logic and Interlocks

A single, documented cause-and-effect matrix (Appendix B format) shall govern the interaction of BMS, fire panel, ventilation, suppression, and electrical isolation. Minimum logic:

- Off-gas confirmed (voted) → container ESD: open container DC isolation, inhibit PCS for that container, start NFPA 69 exhaust, alert 24×7 centre, do NOT release suppression (no fire yet), do NOT stop ventilation.
- Smoke/heat confirmed (cross-zoned) → fire mode: release compartment suppression per agent logic, close/hold ventilation per the documented fire-vs-gas mode decision, notify fire brigade automatically, maintain detection and door-status power (fire-survivable circuits per 4.6).
- Manual ESD stations at the array boundary and control room — clearly a site-level function: one action isolates DC at every container, trips PCS AC breakers, and leaves lighting, detection, ventilation and monitoring alive on the protected supply.
- Restoration interlocked: no re-energisation after any fire-mode event without a documented incident investigation gate (8.4) — automatic auto-reclose of any tripped BESS device is prohibited.

Barrier Model & Risk Assessment

6.1 Bowtie Analysis — Two Separate Top Events

The site risk model shall maintain at minimum two distinct bowties, because the threat lines, barriers, and consequence pathways differ fundamentally. Merging them produces a model that flatters the design and misleads the response plan.

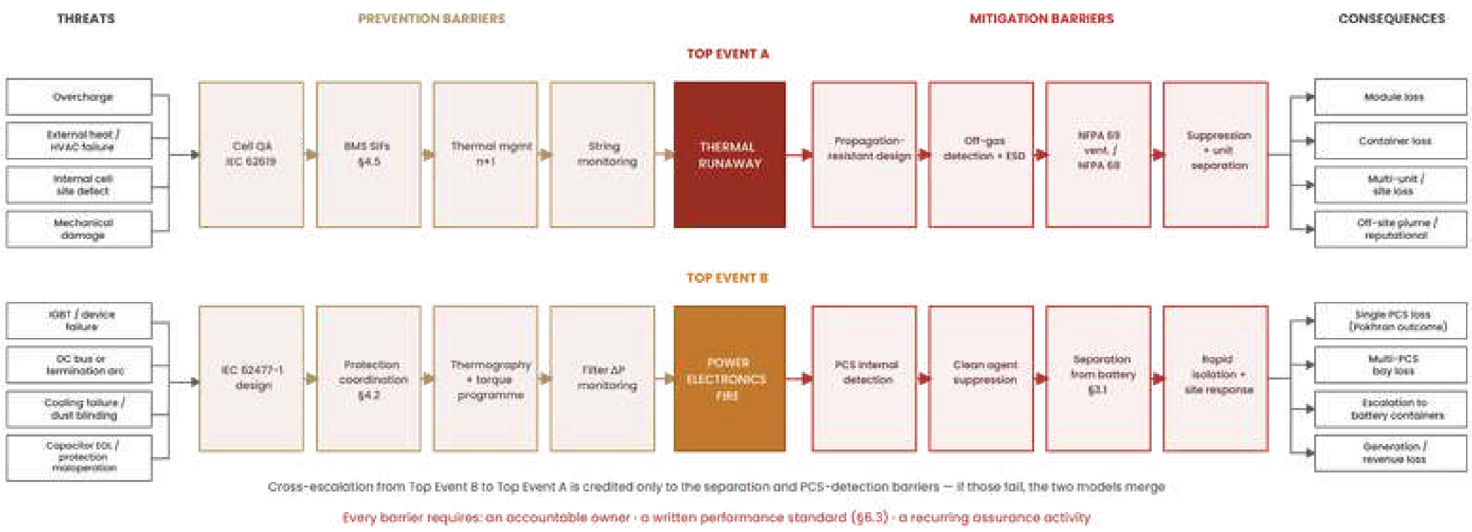
Top Event A — Battery thermal runaway (cell venting escalating beyond one module). Threat lines: overcharge, external heat/HVAC failure, internal cell defect, mechanical damage, external fire impingement. Prevention barriers: cell quality assurance and incoming inspection, BMS SIFs (4.5), thermal management with n+1 capability and failure alarms, charge-window management (SOC caps in high ambient), transport/installation handling controls. Mitigation barriers: propagation-resistant module design (UL 9540A evidence), off-gas detection + ESD, NFPA 69 ventilation, NFPA 68 venting, compartment suppression, unit separation, emergency response. Consequences: single-module loss → container loss → multi-unit/site loss → off-site plume and reputational event.

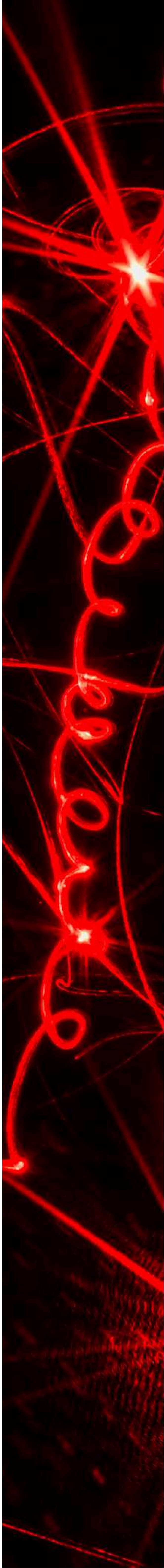
Top Event B — Power electronics / electrical fire (PCS, switchgear, cabling, transformer). Threat lines: IGBT/device failure, DC bus or termination arc, cooling failure/dust blinding, capacitor end-of-life, protection maloperation, rodent/environmental damage. Prevention barriers: IEC 62477-1 compliant design, protection coordination and arc-energy management (4.2), thermography and torque programmes (4.6, 8.2), filter DP monitoring, enclosure sealing/IP maintenance. Mitigation barriers: PCS internal detection and clean-agent suppression, physical separation from battery enclosures (3.1), rapid electrical isolation, on-site first response. Consequences: single-PCS loss (the Pokhran outcome — contained, ~₹20 lakh) → multi-PCS bay loss → escalation to battery containers if separation barriers fail.

Each barrier on both bowties shall carry an owner, a performance standard (6.3), and an assurance activity — a barrier without an assurance task is a line on a diagram, not a safeguard.

Figure 7 — Barrier (Bowtie) Model: Two Independent Top Events

Merging the two models flatters the design and misleads the response plan — each barrier carries an owner, a performance standard and an assurance task



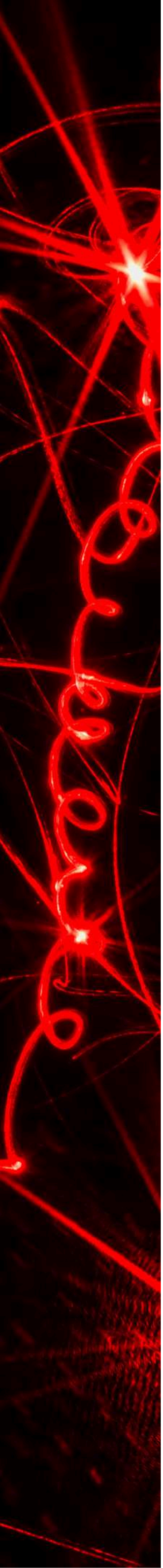


6.2 HAZOP / LOPA Methodology for BESS

- A structured HAZID at concept stage (nodes: site/layout, container, DC system, PCS, MV system, auxiliaries, construction/commissioning phase), followed by full HAZOP at detailed design using guidewords adapted for electrochemical systems (More Charge, No Cooling, Reverse Power, More Gas, No Ventilation, Late Detection).
- LOPA on the scenarios that HAZOP grades above the tolerable line, using project risk criteria agreed with the owner; independent protection layers credited only where independence, specificity, dependability and auditability are demonstrated — the BMS control function and BMS safety function are NOT independent layers unless architecturally separated (4.5).
- SIL targets flowing from LOPA into the safety requirements specification; verification closed at SAT with end-to-end trip records.
- Quantitative fire modelling (radiant flux between units, plume dispersion for toxicity, deflagration overpressure) where layout deviates from default spacing or where AHJ/community consultation requires it.

6.3 Performance Standards for Safety-Critical Barriers

Barrier	Functionality (what it must	Availability / Survivability	Assurance Activity
Off-gas detection + ESD	Detect venting precursors and execute container isolation within defined	Available whenever container energised; powered through ESD	Quarterly gas-response test; annual end-to-end trip
NFPA 69 exhaust ventilation	Hold concentration < 25% LFL at design release rate	Runs during gas mode; supply survives container isolation	Airflow verification annually; damper/interlock function test
Deflagration vent panels	Open at design Pstat; discharge to safe area	Passive; not obstructed, corroded or painted shut	Visual inspection quarterly; restraint check annually



Unit separation / fire walls	Prevent unit-to-unit propagation for design fire	Passive	Layout change control (MOC); barrier integrity survey
Compartment suppression	Release on cross-zoned confirmation; achieve design density/concentration	Auto + manual release; supervised circuits	NFPA 25 / vendor ITM schedule; discharge records
Rack/container DC isolation	Break DC within rating under load and fault	Operable locally and from ESD	Contact resistance + operation test annually
Site firewater	1,900 L/min × 2 h at required pressure	Pump auto-start; storage level	Weekly pump churn; annual flow test
On-site first response	Initiate cooling/isolation within minutes; execute door/standoff	24×7 trained coverage	Quarterly drills incl. one night drill; annual joint drill with fire brigade

Emergency Response & Firefighting Strategy

7.1 Emergency Response Plan, Stranded Energy and Re-ignition

- Site-specific ERP written against both bowtie top events, with distinct doctrines: a PCS/electrical fire is fought (isolate, apply appropriate agent, ventilate smoke); a battery container in confirmed runaway is contained (cool neighbours, protect exposures, let the involved unit burn out under monitoring unless intervention criteria are met).
- Door-opening doctrine: no entry into any container with active or suspected gas alarm until gas-free verification; approach from upwind quarter; assume deflagration potential — this is the direct McMicken lesson and shall be drilled, not merely written.
- Stranded energy: a fire-damaged battery remains charged and unstable. ERP defines the standoff, monitoring (thermal imaging at defined intervals), and the re-ignition watch period of minimum 24–72 hours post-extinguishment before any handling; damaged-unit disposal per vendor stranded-energy procedure and applicable waste rules (India: Battery Waste Management Rules 2022).
- Toxic products (HF, CO) reflected in responder PPE (SCBA mandatory within the hazard area) and in downwind public-protection triggers coordinated with district authorities

7.2 Firewater Run-off and Environmental Containment

- Firewater applied to lithium-ion events entrains metals and fluorides; site grading and kerbing shall direct run-off to a lined containment/evaporation basin sized for the design cooling duration, not to open desert ground or drainage; post-event water tested before disposal per CPCB requirements.
- Transformer oil containment integrated into the same drainage philosophy; oil-water interception where oil-filled plant is retained.

7.3 Mutual Aid and Fire Service Pre-Planning

- •Pre-incident plan lodged with the responding fire station(s): site plan showing ESD stations, isolation points, hydrants, water storage, standoff lines, and the explicit statement of the containment doctrine so external crews do not attempt entry tactics appropriate to structural fires.
- •Annual joint exercise; familiarisation visits at commissioning and after any major site change; in remote districts (e.g., Jaisalmer-class locations with long brigade response times), the on-site capability of 7.1 is the credited barrier and shall be resourced accordingly — the Pokhran event validates the loss-limiting value of a competent in-house team.

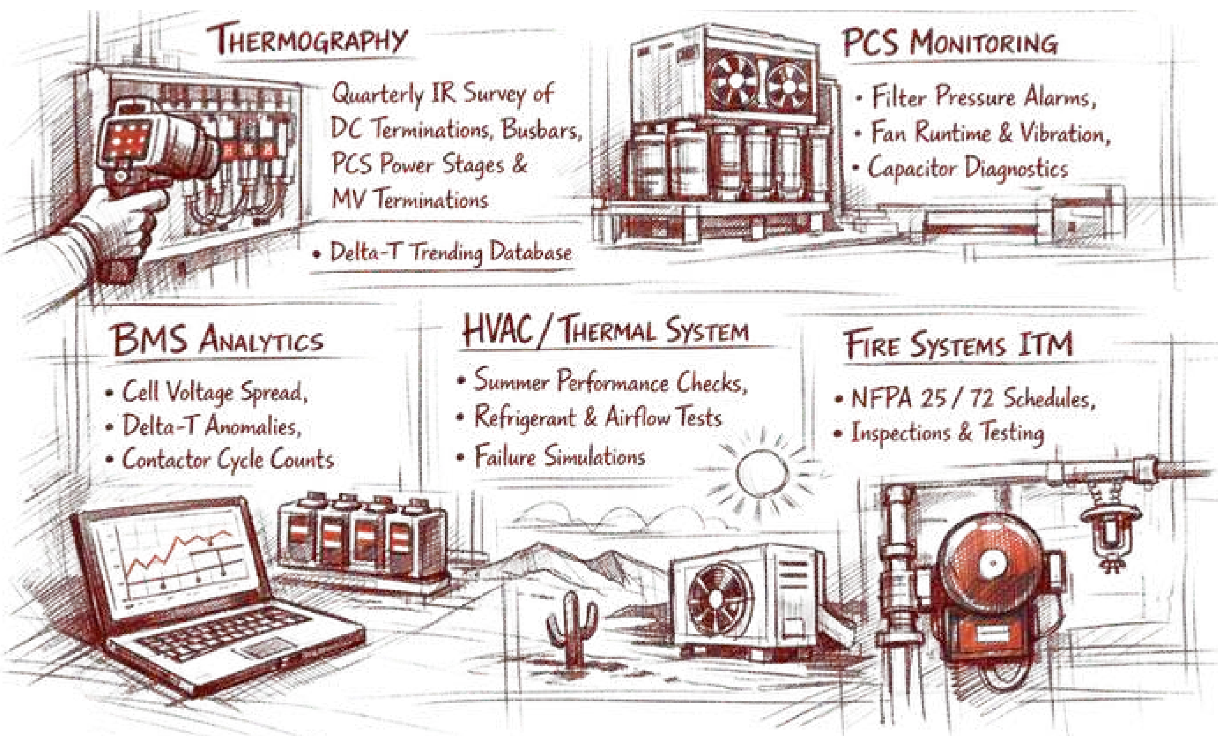
Commissioning, Operations & Maintenance

8.1 Pre-Energisation Checks and FAT/SAT

- FAT at container/PCS factory: BMS protection setpoint verification, contactor and fuse coordination evidence, insulation resistance and hipot records, UL 9540A configuration-equivalence check against supplied build state, detection and suppression panel function.
- SAT on site: earth grid test results vs IEEE 80 design, IMD function, end-to-end SIF trip tests witnessed (4.5), ESD cause-and-effect walkdown against Appendix B, ventilation airflow measurement, detection response tests with test gas/smoke, thermographic baseline at ≥ 80% load, protection relay secondary injection and breaker timing.
- Energisation permit gated on: open-punch-list review (no Category A items), ERP issued and drilled, firewater proven, AHJ/CEIG approvals in hand, insurer inspection closed.

8.2 Predictive and Preventive Maintenance

- Thermography: quarterly IR survey of all DC terminations, busbars, PCS power stages and MV terminations under representative load; trending database with defined delta-T intervention thresholds.
- PCS: filter differential-pressure monitoring with alarm-based replacement, fan runtime and vibration monitoring, capacitor health per vendor ageing model, gate-driver diagnostics review.
- BMS analytics reviewed monthly: cell voltage spread, delta-T outliers, self-discharge anomalies, contactor cycle counts — leading indicators feeding the Section 6 barrier assurance dashboard.
- HVAC/thermal system: performance verification each summer onset for desert sites; refrigerant and airflow checks; failure simulation annually to confirm BMS derating/trip response.
- Fire systems ITM per NFPA 25/72 schedules (or IS equivalents) with records auditable by insurer and AHJ.



8.3 Management of Change and Spares Philosophy

- MOC applies to: firmware (BMS, PCS, EMS), setpoints, cell/module replacements with any revision change, layout or barrier changes, suppression/detection modifications, and operating envelope changes (SOC windows, augmentation). Every MOC screens against both bowties and updates Appendix B where logic changes.
- Spares: minimum stock of PCS power modules/IGBT stacks, gate drivers, fans and filters, contactors, detection heads, and vent panels, sized for the site's brigade-response and logistics reality. The Pokhran restoration-within-a-week outcome was possible because spares existed; the design basis makes that a requirement, not luck.

8.4 Incident Reporting and Investigation

- All fire, gas, ESD and protection-trip events investigated under a defined procedure; root-cause method (e.g., barrier-based/Tripod class) aligned to the bowtie so findings map to barrier failures; lessons routed through MOC.
- Statutory reporting: electrical accidents to the Electrical Inspectorate per CEA Safety Regulations timelines; stock-exchange disclosure discipline for listed owners — accurate, early, and quantitative, so the company narrative leads the media narrative (the Pokhran clarification of 17 July 2026 is the template: state what was affected, what was not, the financial materiality, and the restoration path).

India-Specific Regulatory Overlay

For installations in India, the following statutory layer applies over the consensus standards in this document. Where an Indian statutory requirement is more stringent, it governs; where it is silent (BESS-specific fire protection largely is), this document fills the gap and should be offered to the AHJ as the project's declared basis.

- CEA (Measures relating to Safety and Electric Supply) Regulations, 2023 as amended — electrical safety obligations, periodic inspections, and accident reporting; CEIG approval for MV/HV installations prior to energisation.
- CEA (Technical Standards for Connectivity to the Grid) Regulations and amendments covering energy storage — grid-interface performance, protection, and metering requirements for the PCS and pooling station.

- State Fire Services Act and Fire NOC process — engage the state fire authority early with the hazard mitigation analysis, because most state authorities lack BESS-specific checklists and will otherwise apply building-code assumptions that fit poorly (e.g., occupancy-based sprinkler thinking instead of gas-management logic).
- National Building Code 2016 Part 4 and IS 1646 for site buildings (control room, stores); IS 2189 for detection system installation practice; IS/IEC adoptions of cited IEC standards where notified.
- Battery Waste Management Rules 2022 for damaged-module handling and end-of-life; Hazardous Waste Rules for fire debris and firewater residues; CPCB consent conditions where applicable.
- PESO involvement only where site fuel storage (DG diesel) or compressed gases cross licensing thresholds — the BESS itself is not PESO-licensed, a point worth clarifying with district authorities to avoid mis-scoped objections.
- Environmental and social: district disaster-management-plan integration for large sites, community communication protocol for visible-plume events, and coordination with defence authorities where sites adjoin restricted areas (relevant in Pokhran-class geographies).

Appendix A — Design Verification Checklist (Extract)

#	Verification Item	Reference	Evidence
A1	UL 9540A report configuration matches supplied cell/module/rack/enclosure build state	3.2	Report + build-state comparison sheet
A2	Unit spacing & group sizes vs NFPA 855 or accepted engineered basis	3.1/3.2	Layout drawing + HMA acceptance
A3	Gas management basis declared (NFPA 69 primary + NFPA 68 backstop) with vendor gas data	5.2	Calc note + panel/fan datasheets

A4	Detection layers 1–5 implemented with voting logic	5.1	C&E matrix + panel config
A5	PCS separation from battery enclosures; PCS internal detection/suppression	3.1/4.2/5.3	Layout + PCS GA drawings
A6	DC selectivity study incl. SOC-dependent	4.1/4.4	Coordination study
A7	SIF list, SIL targets, verification calcs, SAT trip records	4.5/6.2	SRS + SAT dossier
A8	Arc-flash study and labelling AC + DC	4.2	Study + site labels
A9	Firewater capacity & delivery proven	3.3/6.3	Flow test records
A10	ERP with dual doctrine, door-opening rule, stranded-energy standoff; drills done	7.1	ERP + drill records
A11	Firewater/oil run-off containment constructed	7.2	As-built drainage drawings
A12	CEIG approval, Fire NOC, insurer inspection closed before	8.1/9	Certificates

Appendix B — ESD Cause & Effect Matrix (Template Skeleton)

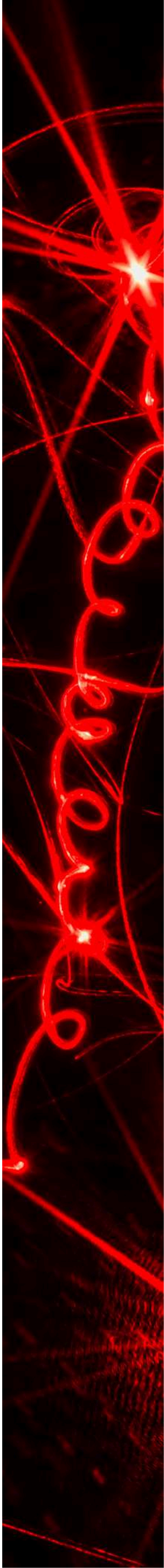
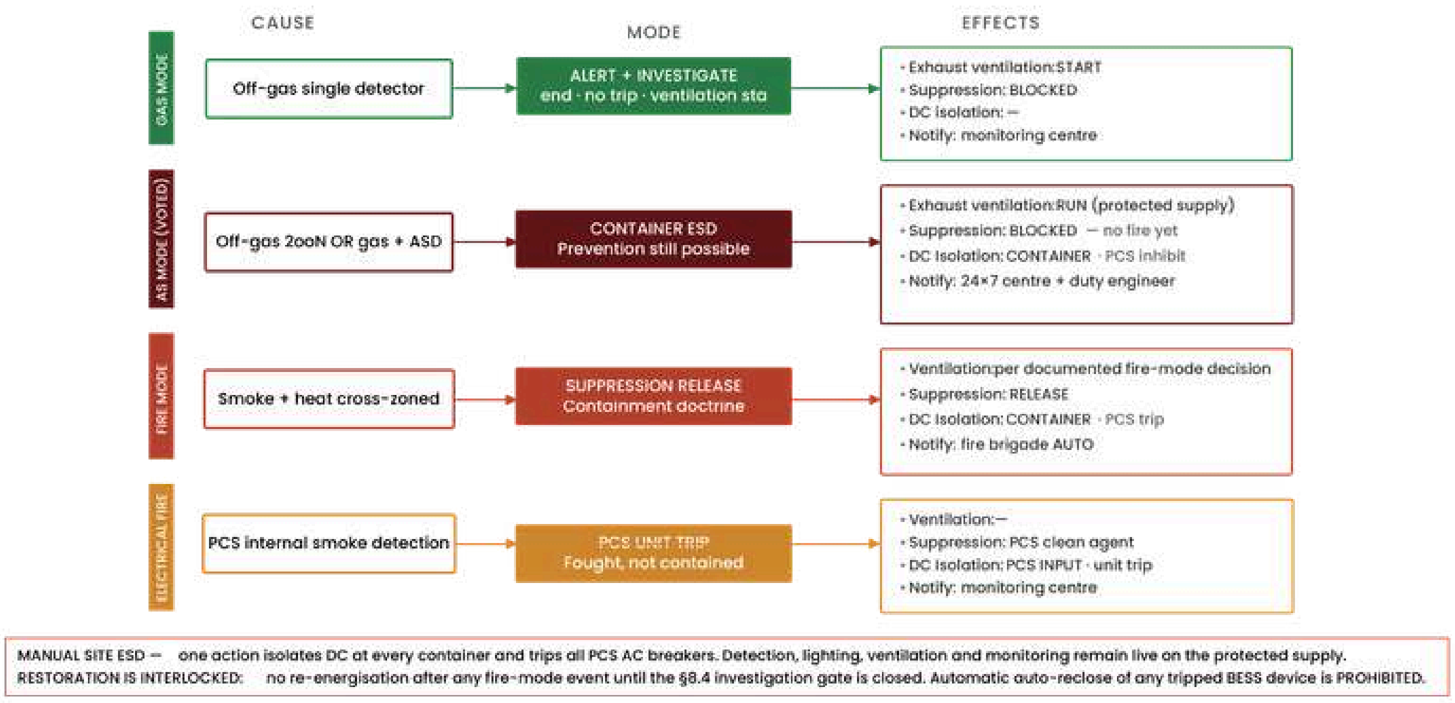


Figure 8 — Detection Voting and ESD Escalation Logic (Cause & Effect Skeleton)

Spurious-trip economics shall not be allowed to erode the single-detector alert function



The project shall complete a full C&E matrix in this structure; the rows below define the mandatory minimum logic of Section 5.5.

Cause (voted as defined)	DC Isolation	PCS Inhibit	Exhaust Vent.	Suppression	Brigade Notify	Notes
Off-gas single detector	—	—	Start	—	—	Alert + investigate; trend
Off-gas voted (2ooN or gas+ASD)	Container	Container	Run	Blocked	Alert centre	Gas mode; ventilation protected supply
Smoke+ heat cross-zoned	Container	Container	Per fire-mode decision	Release	Auto	Fire mode

PCS internal smoke	PCS input	Unit trip	—	PCS clean agent	Alert centre	Electrical-fire doctrine
Manual site ESD	All containers	All units	Run	Manual only	Auto	Detection/lighting stay live
Restoration	Blocked until investigation gate closed (8.4)					No auto-reclose

Appendix C — Deviations Register (Format)

Any departure from this design basis shall be recorded with: clause reference; description of deviation; quantitative justification (test data, modelling, LOPA); compensating measures; approvals (owner's engineer, insurer, AHJ as applicable); and review date. An empty register is a deliverable — it is the auditable statement that the design conforms.

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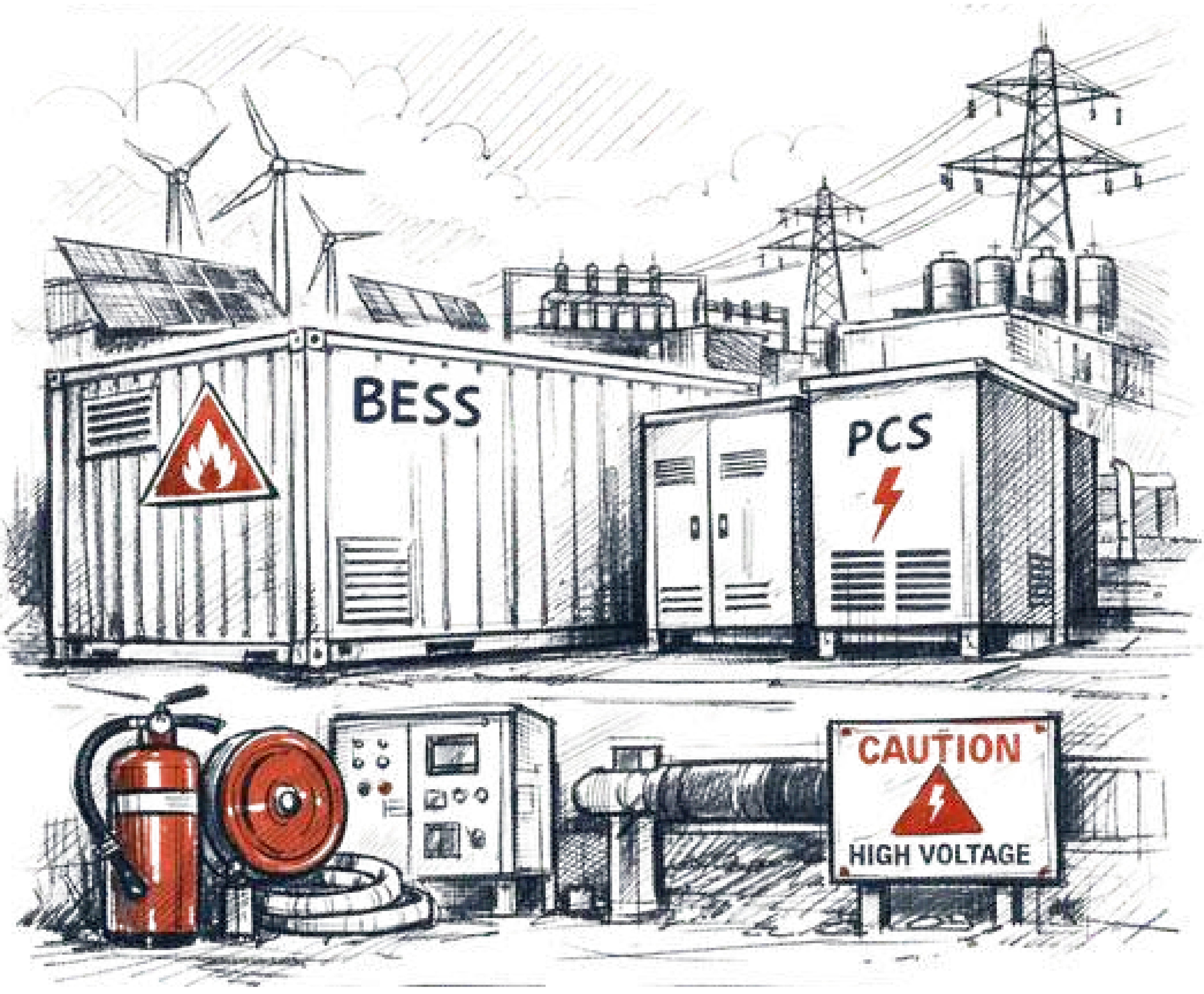

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