Standard Guideline-Enhancing Electrical Safety Standards for Rooftop PV and BESS Installations in ASEAN through Safety Features Application

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About ACE

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Established in 1999, the ASEAN Centre for Energy (ACE) is an intergovernmental organisation within the ASEAN structure that independently represents the interests of the 10 ASEAN countries in the energy sector. The Centre accelerates the integration of energy strategies within ASEAN by providing relevant information and expertise to ensure the necessary energy policies and programmes are in harmony with economic growth and the region's environmental sustainability. It is guided by a Governing Council composed of Senior Officials on Energy leaders from each ASEAN Member State and a representative from the ASEAN Secretariat. Hosted by Indonesia's Ministry of Energy and Mineral Resources (MEMR), ACE's office is located in Jakarta, Indonesia.

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Foreword from ACE

The energy landscape across Southeast Asia is transforming at an unprecedented pace. Guided by ASEAN's shared commitment to sustainability and resilience, rooftop solar photovoltaics (PV) and Battery Energy Storage Systems (BESS) are rapidly moving from niche applications to mainstream solutions. This exciting shift is crucial for meeting our regional energy goals, but it simultaneously demands a heightened focus on the bedrock of any reliable power system: electrical safety.

As the ASEAN Centre for Energy (ACE), we champion this transition, facilitating collaboration and providing critical analysis to support our Member States. However, rapid technological advancement must proceed hand-in-hand with unwavering attention to safety. The electrical safety considerations associated with rooftop PV and BESS are not merely technical details; they are fundamental prerequisites for building enduring public trust, attracting sustained investment, and ensuring the long-term reliability and resilience of our evolving energy infrastructure.

This study provides a timely and essential assessment of the electrical safety landscape for these critical technologies across ASEAN. It delves into the specific hazards – from the persistent DC voltages in PV systems to the thermal complexities of battery storage – and examines the effectiveness of current mitigation strategies and technological safeguards. Critically, it maps the diverse regulatory environments within our region, highlighting both commendable progress in adopting international standards and significant gaps that require concerted action.

The findings underscore the urgent need for enhanced regional cooperation and harmonisation. By strengthening national frameworks, promoting best practices in installation and maintenance, mandating robust safety features, and fostering greater alignment on standards, we can collectively mitigate risks and create a safer environment for all.

ACE is committed to supporting ASEAN Member States in navigating these challenges. We believe this study will serve as a valuable resource, fostering informed dialogue and catalysing the necessary actions to ensure that our clean energy transition is not only swift but also secure and sustainable. Together, let us build an energy future for ASEAN that is innovative, resilient, and, above all, safe.

Dato Ir. Ts. Abdul Razib Dawood

Executive Director of ASEAN Centre for Energy (ACE)

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Abbreviations

A	**AC**	Alternating Current
	ACE	ASEAN Centre for Energy
	ADB	Asian Development Bank
	AENBD	Autoriti Elektrik Negara Brunei Darussalam
	AFCI	Arc Fault Circuit Interrupter
	AFDD	Arc Fault Detection Device
	AFPE	Arc Fault Protection Equipment
	AMEM	ASEAN Ministers on Energy Meeting
	AMS	ASEAN Member State
	ANSI	American National Standards Institute
	APAEC	ASEAN Plan of Action for Energy Cooperation
	APG	ASEAN Power Grid
	AS/NZS	Australian/New Zealand Standard
	ASEAN	Association of Southeast Asian Nations
B	**BCA**	Building and Construction Authority (Singapore)
	BESS	Battery Energy Storage System
	BIPV	Building-Integrated Photovoltaic
	BMS	Battery Management System
	BSN	Badan Standardisasi Nasional (Indonesia)
	BPS	Bureau of Philippine Standards
	B-TMS	Battery Thermal Management System
C	**CAN**	Canadian (referring to standards)
	CECS	China Engineering Construction Standardization Association
	CO	Carbon Monoxide
D	**DC**	Direct Currentw
	DER	Distributed Energy Resources
	DES	Department of Electrical Services (Brunei)
	DOE	Department of Energy (Philippines)
	DTS	Data Transfer Station (likely context)
	DUs	Distribution Utilities (Philippines)
E	**EAC**	Electricity Authority of Cambodia
	ECP	Exposed Conductive Part
	EDC	Electricité du Cambodge
	EDL	Electricité du Laos

	EE&C-SSN	Energy Efficiency and Conservation Sub-Sector Network
	EGAT	Electricity Generating Authority of Thailand
	EIT	Engineering Institute of Thailand
	EMA	Energy Market Authority (Singapore)
	EMC	Electromagnetic Compatibility
	EMS	Energy Management System
	EN	European Norm (Standard)
	ERAV	Electricity Regulatory Authority of Viet Nam
	ERC	Energy Regulatory Commission (Philippines, Thailand)
	ESAH	Electricity Supply Application Handbook (Malaysia)
	ESCOM	Electrical Safety Committee (Brunei)
	ESDM	Ministry of Energy and Mineral Resources (Indonesia)
	ESS	Energy Storage System
	EVN	Viet Nam Electricity
G	**GB/T**	Chinese National Standard (Guobiao/Recommended)
	GFDI	Ground Fault Detection and Interruption
	GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
	GMS	Greater Mekong Subregion
	gPV	Fuse type for PV applications
H	**H_2**	Hydrogen Gas
	HAPUA	Heads of ASEAN Power Utilities/Authorities
	HVAC	Heating, Ventilation, and Air Conditioning
	HV/LV	High Voltage / Low Voltage
I	**IBR**	Inverter-Based Resources
	IEC	International Electrotechnical Commission
	IEEE	Institute of Electrical and Electronics Engineers
	IFC	International Finance Corporation
	IGBT	Insulated Gate Bipolar Transistor
	IIEE	Institute of Integrated Electrical Engineers of the Philippines
	IMD	Insulation Monitoring Device
	IP	Ingress Protection
L	**LEPTS**	Lao Electric Power Technical Standards
	LEW	Licensed Electrical Worker (Singapore)
	LFL	Lower Flammable Limit

	Li-ion	Lithium-ion
	LFP	Lithium Iron Phosphate
	LOTO	Lockout/Tagout
	LV	Low Voltage
M	**MCCB**	Moulded Case Circuit Breaker
	MEA	Metropolitan Electricity Authority (Thailand)
	MEM	Ministry of Energy and Mines (Lao PDR)
	MEMR	Ministry of Energy and Mineral Resources (Indonesia)
	MEPE	Myanmar Electric Power Enterprise
	MME	Ministry of Mines and Energy (Cambodia)
	MOEP	Ministry of Electric Power (Myanmar)
	MOIT	Ministry of Industry and Trade (Viet Nam)
	MPPT	Maximum Power Point Tracking
	MS	Malaysian Standard
N	**NCA**	Nickel Cobalt Aluminium
	NCM	Nickel Cobalt Manganese
	NaS	Sodium-Sulphur
	NEC	National Electrical Code (USA, also basis for PEC)
	NFPA	National Fire Protection Association (USA)
	NGCP	National Grid Corporation of the Philippines
	NMC	Nickel Manganese Cobalt (same as NCM)
O	**OBO**	Office of the Building Official (Philippines)
	O&M	Operation and Maintenance
P	**PCE**	Power Conversion Equipment
	PCS	Power Conversion System
	PEA	Provincial Electricity Authority (Thailand)
	PEC	Philippine Electrical Code
	PEI	Power Electronic Interface
	PELV	Protective Extra-Low Voltage
	PLN	Perusahaan Listrik Negara (State Electricity Company, Indonesia)
	PPE	Personal Protective Equipment
	PV	Photovoltaic
R	**RCD**	Residual Current Device
	RE	Renewable Energy
	REPP-SSN	Regional Energy Policy and Planning Sub-Sector Network
	RE-SSN	Renewable Energy Sub-Sector Network
	RoCoF	Rate of Change of Frequency
	RSD	Rapid Shutdown

S	**SACU**	Station Controller (likely meaning)
	SCDF	Singapore Civil Defence Force
	SEB	Specialised Energy Body
	SEDA	Sustainable Energy Development Authority (Malaysia)
	SELV	Safety Extra-Low Voltage
	SHENA	Safety, Health, and Environment National Authority (Brunei)
	SOC	State-of-Charge
	SOH	State-of-Health
	SOME	Senior Officials Meeting on Energy
	SOP	Standard Operating Procedure
	SPD	Surge Protective Device
	SP Group	Singapore Power Group
	SPPC	Smart Power Plant Controller (likely meaning)
	SPLN	Standar Perusahaan Listrik Negara (PLN Standard)
	SS	Singapore Standard
	SSC	Singapore Standards Council
	SSN	Sub-Sector Network
	ST	Suruhanjaya Tenaga (Energy Commission, Malaysia)
	STS	Static Transfer Switch
T	**T&D**	Transmission and Distribution
	TISI	Thai Industrial Standards Institute
	TNB	Tenaga Nasional Berhad (Malaysia)
	TPES	Total Primary Energy Supply
	TR	Technical Reference (Singapore)
	TRF	Transformer (likely context)
	TUV SUD	Technischer Überwachungsverein Süd (Technical Inspection Association South)
U	**UHV**	Ultra-High Voltage
	UK	United Kingdom
	UL	Underwriters Laboratories (Standards Organisation)
	UPS	Uninterruptible Power Supply
	USA	United States of America
	USAID	United States Agency for International Development
	USD	United States Dollar
	UV	Ultraviolet
V	**VDE**	Verband der Elektrotechnik Elektronik Informationstechnik (German Standards Body)
	VRE	Variable Renewable Energy
W	**WSH**	Workplace Safety and Health (Singapore)
Y	**YESC**	Yangon Electricity Supply Corporation (Myanmar)

Executive Summary

ASEAN's ambitious push towards a sustainable energy future, championed by bodies like HAPUA and ACE under the APAEC framework, hinges significantly on the successful deployment of rooftop solar photovoltaic (PV) and Battery Energy Storage Systems (BESS). While these technologies are pivotal for achieving goals like the targeted 35% renewable energy (RE) share in installed power capacity by 2025, their rapid proliferation across urban and industrial landscapes introduces profound electrical safety imperatives.

This study navigates the critical intersection of technological advancement and safety assurance, revealing crucial insights necessary to underpin public trust and secure regional investment.

The analysis moves beyond general awareness to confront the specific, often unseen, electrical hazards inherent in these systems. Rooftop PV arrays operate under persistent high DC voltages, often reaching from 600 V to 1,500 V whenever sunlight is present, creating latent shock risks for anyone interacting with the system. Furthermore, the threat of DC arc faults – electrical discharges exceeding 3,000°C – looms large, frequently ignited by installation defects or environmental degradation, and proving notoriously difficult to extinguish compared to AC arcs.

For BESS, particularly systems using lithium-ion chemistries, the spectre of thermal runaway – an uncontrollable, self-heating chemical reaction often triggered by internal manufacturing flaws, control system failures, or physical damage – presents a severe fire and explosion risk, escalating rapidly from cell-level failure to system-wide events.

The integration of high levels of these inverter-based resources also introduces novel challenges to grid stability, impacting system inertia and potentially blinding conventional protection systems.

Real-world incidents starkly illustrate these vulnerabilities. Case studies scrutinised from within ASEAN reveal tragedies like installer electrocutions due to proximity to high-voltage lines in Malaysia and the Philippines, fires complicated by the lack of Rapid Shutdown (RSD) capabilities in Malaysia and Thailand, and potential ignition from lightning strikes, where protection was inadequate in Indonesia. Globally, recurring themes emerge, including widespread rooftop fires linked to faulty DC isolators, particularly in Australia, BESS cooling system failures triggering major fires like the Victorian Big Battery incident, and complex integration issues in multi-vendor BESS projects leading to failures in China and Germany.

Addressing these hazards requires a multi-layered approach detailed herein, extending from component-level integrity to system-wide safeguards. Key technological mitigations explored include advanced Arc Fault Circuit Interrupters (AFCIs) designed to detect elusive DC arc signatures, mandatory RSD systems for de-energising arrays, and robust Battery Management Systems (BMS) coupled with effective Battery Thermal Management Systems (B-TMS) to prevent BESS overheating. However, the study reveals that technology alone cannot suffice without rigorous standards and skilled execution.

Crucially, the assessment of ASEAN's regulatory frameworks highlights a significant disparity. While nations like Singapore, Malaysia, and Thailand demonstrate well-structured approaches aligned with international benchmarks like IEC 60364-7-712 and IEC 62933 series, a considerable gap persists elsewhere. Many Member States lack detailed national codes for critical areas, notably BESS installation safety (covering thermal/chemical risks akin to NFPA 855) and tailored requirements for rooftop PV grounding and lightning protection in ASEAN's high-risk climate. In these contexts, safety often relies on inconsistent project-based enforcement or financier mandates. This assessment strongly indicates that strengthening national regulations and fostering regional harmonisation are essential next steps to ensure these transformative technologies are deployed safely and sustainably.

Chapter 1

Introduction

1.1. Background

ASEAN's journey towards a sustainable and integrated energy future is propelled by a well-established collaborative framework involving key regional bodies. The Heads of ASEAN Power Utilities/Authorities (HAPUA), acting as a Specialised Energy Body (SEB), play a vital role, specifically tasked with advancing the ASEAN Power Grid (APG) programme area under the region's energy cooperation blueprint. HAPUA focuses on enhancing regional energy security through grid interconnection development, promoting multilateral electricity trade, and working towards harmonising technical standards and operating procedures.

Complementing HAPUA are various Sub-Sector Networks (SSNs), such as those dedicated to Renewable Energy (RE-SSN), Energy Efficiency and Conservation (EE&C-SSN), and Regional Energy Policy and Planning (REPP-SSN). These SSNs are the implementing arms for specific programme areas outlined in the guiding policy document, the ASEAN Plan of Action for Energy Cooperation (APAEC). [1], [2]

Supporting these efforts is ACE, which serves as a crucial catalyst, knowledge hub, and think tank. ACE facilitates multilateral collaboration, provides technical expertise and policy analysis, manages regional energy data, and actively supports HAPUA and the SSNs in implementing the APAEC framework, often serving secretariat functions. This coordinated structure, operating under the guidance of the ASEAN Ministers on Energy Meeting (AMEM) and the Senior Officials Meeting on Energy (SOME), drives the region's energy agenda.

The current iteration, APAEC Phase II: 2021-2025, sets ambitious targets critical for the region's sustainable development, including achieving a 23% RE share in the Total Primary Energy Supply (TPES) and 35% in installed power capacity by 2025. It emphasises enhancing energy connectivity and market integration to ensure energy security, accessibility, affordability, and sustainability for all Member States.

Key initiatives under APAEC Phase II include accelerating APG development, expanding multilateral electricity trading, promoting large-scale RE deployment, enhancing energy efficiency, and advancing regional energy policy and planning.

Achieving these ambitious goals requires not only coordinated policy and technological advancements, but also substantial investment and accelerated deployment of technologies like rooftop solar PV and Battery Energy Storage Systems (BESS). However, the current pace suggests the 23% TPES target might only be reached later.

Ramping up deployment hinges significantly on creating a secure and reliable operating environment. This study focuses on a critical enabler for this acceleration: electrical safety. Robust safety frameworks enhance investor confidence by de-risking projects, ensuring the sustainable and reliable operation of RE assets, and building public trust, all of which are essential for attracting the investment needed to meet APAEC targets. Furthermore, harmonised safety standards facilitate regional cooperation and integration that are central to the APAEC vision.

1.2. Rise of Rooftop PV and BESS in ASEAN and the Imperative for Safety

Parallel to the strategic regional goals, the adoption of rooftop PV and BESS across the AMS is experiencing significant momentum. This growth is propelled by a number of factors, including escalating energy demand from urbanisation and industrialisation, the declining costs of solar panels and batteries, increasing awareness of environmental issues, and national policies supporting distributed generation. Rooftop PV systems offer consumers and businesses the opportunity to reduce electricity costs, enhance energy independence, and contribute to national RE targets, while BESS provides solutions for energy storage, backup power, and improved grid integration. ASEAN countries benefit from high solar irradiation levels, making rooftop solar a particularly viable option.

However, this rapid expansion of distributed solar and storage technologies introduces complex electrical safety challenges that must be proactively managed. Rooftop PV systems operate at high DC voltages (often 600 V-1,500 V) that remain present whenever there is sunlight, creating persistent shock hazards for installers, maintenance personnel, and emergency responders. Furthermore, the DC nature of these systems makes them susceptible to DC arc faults – sustained electrical discharges that generate intense heat (>3,000^{0}C) and are a primary cause of PV-related fires. Installation errors like poor connections, damaged cables, or faulty components can initiate these arcs.

Lithium-ion batteries, the predominant chemistry used in BESS, carry inherent risks, most notably thermal runaway – a dangerous chain reaction where internal cell failures lead to overheating, off-gassing of flammable electrolytes, and potentially fire or explosion. Incidents globally have highlighted risks stemming from manufacturing defects, inadequate thermal management, control system failures, or physical damage.

Given that these systems are often installed on or near occupied buildings, the consequences of electrical failures can be severe. Ensuring electrical safety is, therefore, not merely a technical requirement, but a fundamental necessity. It is crucial for protecting lives and property, maintaining the operational reliability of these valuable energy assets, building enduring public trust in RE technologies, and preventing safety incidents that could impede the progress of the energy transition across ASEAN.

This study directly confronts these safety imperatives. It undertakes a thorough examination of the electrical safety landscape for rooftop PV and BESS in ASEAN, moving from foundational principles and international standards to specific technological hazards, real-world incident analysis, and a critical assessment of the region's regulatory preparedness.

1.3. Objectives

To address the critical need for enhanced electrical safety in ASEAN's growing rooftop PV and BESS sector, this study aims to achieve these specific objectives:

Enhance Understanding of Electrical Safety Issues: To establish a clear foundation by detailing the fundamental electrical hazards, including electric shock, arc flash, arc blast, and fire risks, specifically as they apply to rooftop PV and BESS systems. This involves defining electrical safety in this context and analysing how the unique characteristics of these technologies influence risk profiles. Furthermore, this objective includes examining the emerging system-level safety considerations and grid stability challenges presented by the increasing penetration of inverter-based resources like PV and BESS. A solid grasp of these fundamentals is essential before analysing specific system failures or regulatory needs.

Analyse System-Specific Hazards and Mitigation Features: To provide a detailed technical understanding by investigating the typical architectures of rooftop PV and BESS installations, and identifying the concrete electrical safety risks associated with each component and stage (e.g., DC arc faults in PV wiring, thermal runaway in battery cells, grounding faults, installation errors). This objective involves evaluating common failure modes and their consequences through critically analysing relevant safety incident case studies from ASEAN, and globally. By learning from these real-world events, the study aims to highlight the practical importance and effectiveness of specific mitigation technologies and safety features, such as Arc Fault Circuit Interrupters

(AFCIs), Rapid Shutdown (RSD) systems, robust Battery Management Systems (BMS), and appropriate thermal management and fire detection/suppression systems.

Assess and Map ASEAN's Electrical Safety Frameworks: To evaluate the current state of preparedness across the region by conducting a comprehensive assessment of the existing electrical safety standards, regulations, codes, and governance structures pertaining to rooftop PV and BESS installation and operation within each AMS. This involves benchmarking national approaches against established international standards (e.g., IEC 60364, IEC 62933, IEC 62619, NFPA 855) to identify alignment, deviations, and critical gaps. A clear understanding of the regulatory landscape—including the roles of national bodies and the effectiveness of enforcement mechanisms—is essential for identifying areas in need of improvement and supporting regional harmonisation.

Develop Recommendations for Harmonisation and Improvement: To translate the analysis into practical outcomes by formulating evidence-based, actionable recommendations tailored to the ASEAN context. Based on the synthesised findings regarding hazards, mitigation technologies, incident lessons, and regulatory gaps, this objective proposes concrete strategies for enhancing electrical safety practices across the region. Recommendations will target areas such as adopting specific international standards, developing or refining national codes, strengthening installer certification and training programmes, improving inspection and maintenance protocols, promoting the deployment of advanced safety technologies, fostering better stakeholder coordination, and ultimately moving towards greater harmonisation of safety frameworks to support the secure and sustainable growth of rooftop PV and BESS throughout ASEAN.

1.4. Methodology

This document employs a multi-faceted analytical approach to comprehensively address electrical safety for rooftop PV and BESS in ASEAN. The findings presented in subsequent chapters are derived through the following integrated methods:

Foundational Knowledge Synthesis (Informing Chapter 2): Established electrical safety principles, definitions of hazards (shock, arc flash, fire), and fundamental protective measures are synthesised based on authoritative literature, including core international standards (e.g., IEC 60364 series) and established electrical safety handbooks. This phase establishes the theoretical groundwork for understanding PV and BESS safety challenges. Emerging grid stability and protection issues arising from high RE penetration are analysed based on recent technical papers and reports.

Technology-Specific Hazard Analysis and Empirical Review (Informing Chapter 3): The specific architectures of rooftop PV and BESS systems are detailed. Potential electrical safety hazards unique to these technologies (e.g., persistent DC voltage, DC arc faults, thermal runaway, component failures, installation errors) are systematically identified and analysed, drawing upon technical documentation, manufacturer specifications, and safety reports. Crucially, this analysis is contextualised by evaluating documented safety incidents (case studies) from both within ASEAN and globally. These case studies are analysed to identify root causes, contributing factors (installation quality, component failure, environmental factors, lack of specific safety features like RSD/AFCI), and derive practical lessons learned applicable to the ASEAN context.

Comparative Regulatory and Standards Assessment (Informing Chapter 4): A comprehensive review of the key international electrical safety standard framework relevant to PV (IEC 60364-7-712, IEC 62548, IEC 63027, etc.) and BESS (IEC 62933 series, IEC 62619, NFPA 855, UL 9540A, etc.) is conducted to establish a benchmark of best practices. Against this benchmark, the existing national regulations, electrical codes, grid codes, and technical guidelines pertaining to PV and BESS electrical safety installation are assessed for each AMS. This involves mapping the relevant governance structures and stakeholder roles. A comparative analysis identifies critical gaps, inconsistencies, and areas where national frameworks diverge from or lag behind international standards and best practices, particularly concerning specific hazards like rooftop grounding/ lightning protection and detailed BESS thermal/chemical safety installation requirements.

Synthesis and Strategy Formulation (Informing Chapter 5): The findings from the foundational review, hazard analysis, case study evaluation, and regulatory assessment is synthesised. Based on this integrated analysis, actionable recommendations and strategies tailored to the ASEAN context are proposed. These will focus on enhancing electrical safety practices, addressing identified gaps in standards and regulations, strengthening stakeholder coordination and capacity-building, and promoting the adoption of advanced safety technologies and harmonised frameworks across the region.

Chapter 2

Electrical Safety Features and Safety Issue for Rooftop PV and BESS

As rooftop photovoltaic (PV) systems and battery energy storage systems (BESS) become more widespread across ASEAN nations, ensuring electrical safety is increasingly critical. While these technologies play a vital role in the region's energy transition, they also introduce specific safety challenges that build on core electrical safety principles. This chapter presents those foundational principles, defines electrical safety in the context of PV and BESS, identifies key hazards, explores protective measures, and examines emerging issues unique to these installations. A solid understanding of these fundamentals is essential to reducing risks and ensuring the safe, reliable operation of these systems.

2.1. Definitions and Hazards for Electrical Safety

2.1.1. Defining Electrical Safety

While a single, universal definition of electrical safety can be elusive in theoretical literature, its core concept revolves around recognising the inherent hazards of using electrical energy and implementing precautions to prevent these hazards from causing injury, death, or significant property damage.

In the specific context of PV and BESS installations, a more technical definition applies: Electrical safety encompasses the comprehensive framework of standards, regulations, design principles, installation practices, operational procedures, and maintenance protocols specifically aimed at preventing harm from electrical hazards such as shocks, fires, arc flashes, and explosions. This framework is not static; it must be applied throughout the entire lifecycle of the PV or BESS system – from the initial design and component selection, through careful installation and commissioning, to ongoing operations, inspections, and maintenance.

The mandatory nature of electrical safety measures stems directly from the unique characteristics of electricity as a potent hazard. Unlike many other energy forms, electricity is often invisible, silent, and capable of causing severe harm instantaneously upon unintended contact or system failure. Therefore, electrical safety is not merely a best practice, but a fundamental requirement for any electrical installation, including modern renewable energy (RE) systems like rooftop PV and BESS. Its goal is twofold:

- **Protecting People**: Preventing electric shock, burns, and other injuries to installers, maintenance personnel, building occupants, and the general public.
- **Protecting Systems and Property**: Preventing damage to the PV/BESS equipment itself, connected loads, buildings, and surrounding infrastructure from events like electrical fires or component failures, including prevent cascading power loss/outages.

2.1.2. Fundamental Electrical Hazards

Electricity presents three primary potential hazards relevant to PV and BESS systems.[3] These three hazards—shock, arc flash, and blast—highlight why rigorous adherence to safety standards, proper installation techniques, use of appropriate personal protective equipment (PPE), and regular maintenance are non-negotiable aspects of working with PV and BESS systems.

Electric Shock: This is the physiological reaction or physical stimulation that occurs when electric current passes through the human body. The path the current takes depends on the body's resistance along various potential routes, with the final trauma often determined by the most critical path (the shock circuit). According to Ohm's Law ($V=I\times R$), for a constant voltage (V), the current (I) flowing through the body is inversely proportional to the body's resistance (R). A reduction in body resistance (e.g., due to wet conditions or lack of insulating protective equipment) allows a higher current to flow, leading to more severe injury.

Symptoms of electrical shock can vary widely, from a mild tingling sensation to involuntary and violent muscle contractions, cardiac arrhythmia (irregular heartbeat), respiratory arrest, or significant tissue damage and burns.

Electric Arc (Arc Flash): An electric arc is formally defined as a discharge of electricity through a gas, normally characterised by a voltage drop near the cathode approximately equal to the ionisation potential of the gas. [4] Essentially, it occurs when a significant electric current flows through a path that was previously insulating, typically air. This current flows through the vaporised arc terminal material and ionised air particles. Arcs can be initiated in several ways, including:

- When voltage between points exceeds the air's dielectric strength (e.g., during lightning strikes or switching surges).
- When air becomes superheated by current passing through a conductor (e.g., a thin wire melting under excessive current).
- When contacts carrying high current are separated, superheating the last point of contact. Arcs produce extremely high temperatures, potentially reaching from 20,000 K to 50,000 K at the terminals. This intense heat poses significant dangers:
- It can cause severe, life-threatening burns on exposed skin even at considerable distances (e.g., second-degree burns reported up to 3.6 meters or more).
- It can easily ignite virtually all types of clothing fibres; non-flame-resistant clothing will continue to burn even after the arc ceases, worsening injuries.
- Arc faults are a known cause of fires in PV systems, often resulting from installation errors or product defects. Technologies like AFCIs are vital for detecting and interrupting arcs to prevent fires.

Blast: Often accompanying high-energy electric arcs, a blast is the physical explosion resulting from the arc's effects. The instantaneous superheating of air by the arc causes rapid expansion, creating a pressure wave that can reach 4.79 to 9.58 kPa (100 to 200 lb/ft^2). This pressure is sufficient to:

- Explode electrical equipment like switchgear.
- Turn sheet metal panels into dangerous shrapnel.
- Propel hardware like bolts or screws like bullets.
- Push over structures like concrete block walls.
- Spray molten metal at high velocity.

While not every arc produces a significant blast, when one does occur, it can be extremely destructive and lethal.

2.2. Protective Measures and Components of Electrical Safety

Preventing electrical hazards involves protecting against two main types of contact:

- Direct Contact: Accidental contact with parts that are normally energised, like conductors, terminals, or bus bars.
- Indirect Contact: Contact with exposed conductive parts (ECPs) of equipment (like enclosures) that

are not normally live, but have become energised due to a fault, typically an insulation failure. Indirect contact is particularly insidious as it can occur during normal equipment use.

Effective electrical safety relies on implementing layers of protection, often referred to as safety components or measures, targeting both direct and indirect contact, which is further described in Table 2-1. Proper installation, regular maintenance, adherence to standards, and the use of appropriate safety equipment are all crucial for ensuring these protective measures remain effective throughout the lifespan of PV and BESS installations.

Table 2-1 Components of Protective Measures for Electrical Safety

Function	Components (Measures)	Description
Prevent Direct Contact	Insulation	Basic insulation completely covers live parts, preventing contact. It's the fundamental protection against direct contact and should only be removable by destruction. Functional insulation separates parts at different potentials within equipment.
	Enclosures and Barriers	Physical constructions firmly fixed to prevent accidental touching of live parts without tools. Enclosures surround equipment, while barriers might block access to specific areas.
	Protection by Obstacles	Elements like fences or screens that increase the distance to live parts, keeping them out of normal reach. This offers limited protection (mainly against accidental touch) as obstacles can be circumvented and are typically used only in areas accessible to skilled electrical personnel.
	Additional Protection by Residual Current Devices	Residual Current Devices (RCDs), provide supplementary protection against direct contact, especially in high-risk situations. RCDs operating at ≤30 mA are particularly important in residential settings
Prevent Indirect Contact	Protection by Automatic Supply Disconnection	This active measure limits the duration of dangerous touch voltages on faulty ECPs. Protective devices (like circuit breakers or RCDs) detect fault currents and rapidly disconnect the supply before harmful physiological effects occur. The tripping time must be inversely proportional to the touch voltage.
	Protection Without Automatic Disconnection	Passive measures used where continuity of service is critical (e.g., certain industrial or medical applications). These rely on methods like reinforced insulation or electrical separation to prevent hazardous voltages from appearing on ECPs, even during a fault, often requiring strict supervision by skilled personnel.

2.3. Electrical Safety Standards for Rooftop PV and BESS Installation

Given the potential hazards, establishing standardised approaches to electrical safety is crucial for ensuring consistent, reliable protection across different installations, manufacturers, and jurisdictions. Electrical safety standards are formalised documents outlining the minimum technical requirements, design specifications, testing procedures, and safety practices necessary to mitigate electrical risks associated with equipment and installations. They provide a common technical language and benchmark for manufacturers, installers, regulators, and users.

Electrical safety standards are fundamental, as they establish accepted minimum requirements to protect against hazards like shock and fire, ensuring baseline safety for products and installations. They promote consistency in design and installation practices, guarantee interoperability between equipment and the grid (crucial for PV/BESS), facilitate market access for manufacturers by providing recognised benchmarks, and often form the technical basis for legally enforceable national regulations. In essence, standards create a vital framework for safety, reliability, and market confidence in electrical technologies.

Two primary international organisations develop foundational standards widely used in the electrical and electronics fields, including for PV and BESS safety:

- IEC (International Electrotechnical Commission): Focuses on developing global standards for electrical, electronic, and related technologies. IEC standards are widely adopted or referenced worldwide, particularly for equipment safety, installation practices, and performance.
- IEEE (Institute of Electrical and Electronics Engineers): A professional organisation that develops standards, particularly prominent in power systems, telecommunications, and computing. IEEE standards often focus on interconnection, operation, and system-level aspects.

While IEC and IEEE provide global benchmarks, individual countries, or regions like the AMS often develop their own national electrical codes or standards. These frequently adopt IEC or IEEE standards directly, adapt them with modifications to suit local conditions (e.g., environmental factors, existing infrastructure, regulatory policies), or develop unique standards where international ones are lacking. Harmonising these national standards, often by aligning with international norms, is a key goal for regions like ASEAN to streamline practices and facilitate the deployment of technologies like PV and BESS.

Table 2-2 highlights some critical international standards focusing on the installation and system safety aspects of rooftop PV and BESS. Adherence to these standards during design and installation is fundamental to preventing incidents and ensuring the long-term safe operation of rooftop PV and BESS systems, both within the ASEAN region and globally.

Table 2-2 Relevant Electrical Safety Standards for PV/ BESS Installation

Scope of Standards	Name of Standards	Topic of Standard & Relevance to PV/BESS Installation Safety
General Installation Safety	IEC 60364 series (esp. Part 7-712 for PV)	Fundamental standard for low-voltage electrical installations. Part 7-712 explicitly addresses requirements for PV power supply systems, covering aspects like protection against shock, overcurrent, cable selection, and earthing.
Grid Interconnection	IEEE 1547 series	Crucial for North America and influential globally, this standard defines technical requirements for interconnecting distributed energy resources (DER) like PV and BESS with the grid, focusing on safety, reliability, and interoperability.
PV Array Design	IEC 62548 series	Specifies design requirements for the PV arrays themselves, including aspects like mounting, wiring, and safety considerations specific to the DC side of the system.
Battery Energy Storage Systems	IEC 62933 series	A comprehensive series dedicated to electrical Energy Storage Systems (ESS). It covers various aspects including terminology, safety requirements (e.g., IEC 62933-5-1, -5-2), testing, installation, and environmental issues relevant to BESS.

Arc Fault Protection	IEC 63027, UL 1699B	Addresses the specific hazard of DC arc faults in PV systems by defining requirements for AFCI designed to detect and interrupt such arcs.
Enclosure Protection	IEC 60529	Defines the IP (Ingress Protection) rating system, classifying the degree of protection provided by enclosures against intrusion of solid objects (like dust) and water. Essential for ensuring the durability and safety of outdoor equipment.
Component Safety	IEC 62109 series	Safety standard for power conversion equipment used in PV systems, such as inverters. Covers general safety requirements and specific requirement for inverters.

2.4. Emerging Electrical Safety Aspects from High RE Penetration

The rapid expansion of RE integration, particularly variable sources like solar PV and wind connected via Power Electronic Interfaces (PEIs) or Inverter-Based Resources (IBRs), presents new challenges for electrical safety, grid stability, and reliability, especially as they displace traditional synchronous generators. [5] These challenges have profound implications and require careful consideration, particularly in regions like ASEAN that are pursuing ambitious RE targets.

a. Grid Stability Challenges due to PEI Characteristics

Reduced System Inertia and Frequency Instability: PEIs lack the rotating mass of synchronous generators, reducing the grid's overall inertia. This makes grid frequency more sensitive to power disturbance (e.g., generator trips, large load transient changes, DC faults on power transfer lines), increasing the risk of rapid frequency deviations (Rate of Change of Frequency - RoCoF) and potentially leading to instability or load shedding. Conventional PV & ESS systems often cannot provide inherently sufficient inertial and primary frequency response.

Voltage Instability and Control Issues: PEIs have different reactive power capabilities and fault current characteristics, as compared to synchronous machines. High RE penetration can strain voltage regulation, especially in weak grids or over long transmission distances. Issues like insufficient reactive power support can lead to voltage instability or even collapse during disturbances. RE integration at high penetrations can weaken voltage stability.

Transient Overvoltage: Certain grid faults (e.g., UHV DC commutation failures) can cause transient overvoltages, which are potentially worsened by the slower or limited reactive power response of some PEI-based systems, as compared to synchronous generators.

Wideband Oscillations: The complex interaction of numerous PEIs can introduce negative damping across various frequencies, potentially leading to harmful sub-synchronous or super-synchronous oscillations that can damage grid equipment like transformers and generators and threaten grid stability.

Weak Grid Adaptability: As renewable energy penetration increases, the power grid becomes weaker, making it difficult for power electronic interfaces (PEIs) to remain stable and connected during voltage fluctuations. In particular, PEIs that lack grid-forming capability will struggle to operate reliably when the short-circuit ratio (SCR) at the point of grid connection falls below 2.

Not Enough Black Start Resources in the System: In systems with high levels of RE penetration, more conventional power plants are likely to retire. However, the inverter-based resources (IBRs) replacing them typically lack black start capability. As a result, a system with insufficient black start resources would take significantly longer to recover during a blackout.

Negative Impedance Worsening Power Oscillation Damping: PEIs with different control schemes would not coordinate, and sometimes together pose a negative impedance for oscillation between 0.1kHz and 1kHz, which would worsen correlating power oscillation. The undamped oscillation would lead to cascading instability to the system.

b. Impact on Protection System

Changes in Fault Current Levels: IBRs typically contribute significantly less fault current compared to synchronous generators, and their contribution can vary. This reduction can cause conventional overcurrent protection relays to fail to detect faults (blinding) or operate incorrectly. Conversely, the bi-directional power flow capability can also lead to false tripping (sympathetic tripping) of relays on healthy lines.

Protection Coordination Challenges: Variable fault levels make coordinating protection devices (e.g. fuses, breakers, reclosers) more complex. Issues like unsynchronised reclosing can occur if a distributed generator continues energising a fault after the main grid breaker opens, potentially damaging equipment upon reclosure.

Need for Advanced Protection: These challenges necessitate a move towards more advanced, potentially adaptive, protection schemes, possibly utilising communication systems and sophisticated algorithms capable of handling low fault currents and complex grid dynamics.

c. Specific BESS Safety Considerations

Thermal Runaway and Fire Risk: Lithium-ion batteries, commonly used in BESS, carry the risk of thermal runaway—a self-sustaining reaction, where overheating in one cell triggers adjacent cells, potentially leading to fire, explosion, and the release of toxic and flammable gases. Flammable and toxic gases commonly found during thermal runaway are CO, H_2, C_XH_Y, and they can further exacerbate the situation if those gases are not properly handled. Overcharging, internal defects, or physical damage can initiate this. BESS fires can be difficult to extinguish and may re-ignite.

Component Failures and Chemical Hazards: Electrical faults (short circuits, insulation breakdown), mechanical failures (impacts, vibration), and environmental factors (heat, humidity) can compromise BESS integrity, leading to malfunctions or leaks of hazardous chemicals.

System Design and Siting: Preventing fire propagation requires careful system design, including adequate segregation between modules/racks, effective off-gas management, and sufficient separation distances between BESS containers and other equipment/buildings, guided by standards like NFPA 855 and UL 9540A. Ventilation and emergency response planning are also critical.

Decommissioning and End-of-Life Management: A critical aspect of the BESS lifecycle is the decommissioning phase. This requires establishing robust procedures for the safe handling, recycling, or disposal of hazardous materials to mitigate long-term environmental impacts and ensure personnel safety when a battery reaches its end-of-life.

d. ASEAN Context Specifics

Grid Constraints and Infrastructure: Existing grid infrastructure limitations, especially at the national level, can constrain RE integration and BESS deployment, sometimes leading to curtailment. Strengthening and digitising the grid is crucial.

Climate Factors: High humidity, heavy rains, and high ambient temperatures in the ASEAN region can exacerbate electrical safety risks, increasing potential for malfunctions, insulation degradation, and overheating, especially for outdoor installations.

Existing Safety Landscape: Many ASEAN countries already face challenges with electrical safety, evidenced by incidents linked to overloaded circuits, faulty wiring, and short circuits, sometimes involving RE systems. Improper installations and lack of robust oversight can significantly raise risks as VRE deployment scales up.

Human Capital and Public Awareness: A significant regional challenge is the shortage of skilled manpower for the proper installation, maintenance, and operation of PV and BESS systems. Compounding this issue is a general lack of public awareness regarding the safety protocols and potential hazards of these technologies, particularly for residential or domestic applications.

Decentralised Systems: The push for decentralised energy access in ASEAN introduces challenges in ensuring safety standards and integration for numerous smaller systems, often in remote areas.

Addressing these emerging safety aspects requires a multi-faceted approach, including developing and enforcing robust, updated grid codes and standards tailored for high PEI penetration; deploying advanced technologies like grid-forming inverters, enhanced protection systems, and BESS for grid support; ensuring proper installation, commissioning, and maintenance practices; strengthening regulatory oversight, possibly through dedicated agencies [6]; and investing in grid modernisation and regional cooperation initiatives like the APG. Prioritising these electrical safety considerations is essential for a secure, reliable, and sustainable energy transition in ASEAN and globally.

Chapter 3

Electrical Safety Issues and Features for Rooftop PV and BESS

This chapter delves into the architecture, potential electrical safety hazards, relevant case studies, and applicable technical standards associated with rooftop PV systems and BESS. Understanding these aspects is crucial for ensuring safe design, installation, operation, and maintenance.

3.1. System Architecture

PV systems are broadly categorised as utility-interactive (grid-connected) or stand-alone (off-grid). They utilise PV modules arranged in arrays to generate DC power. BESS are often found in stand-alone systems and increasingly in grid-connected systems to provide backup power, peak shaving, energy arbitrage, ancillary services, demand response, and microgrid. Based on installation location, PV systems can be ground-mounted, floating, or rooftop. Rooftop PV systems are common for residential, commercial, and industrial applications, aiming to reduce electricity costs, provide backup power, and sometimes sell excess energy to the grid.

3.1.1. Rooftop PV Systems

Rooftop PV systems convert sunlight into usable AC electricity through several stages and components, as illustrated in Figure 3-1. It depicts a simplified layout showing the path from PV modules (A), through DC wiring (B), a DC disconnect (C), the inverter (D), an AC disconnect (E), a utility disconnect (F), and finally connecting to the building's service entrance (G). It highlights the separate DC and AC grounding connections.

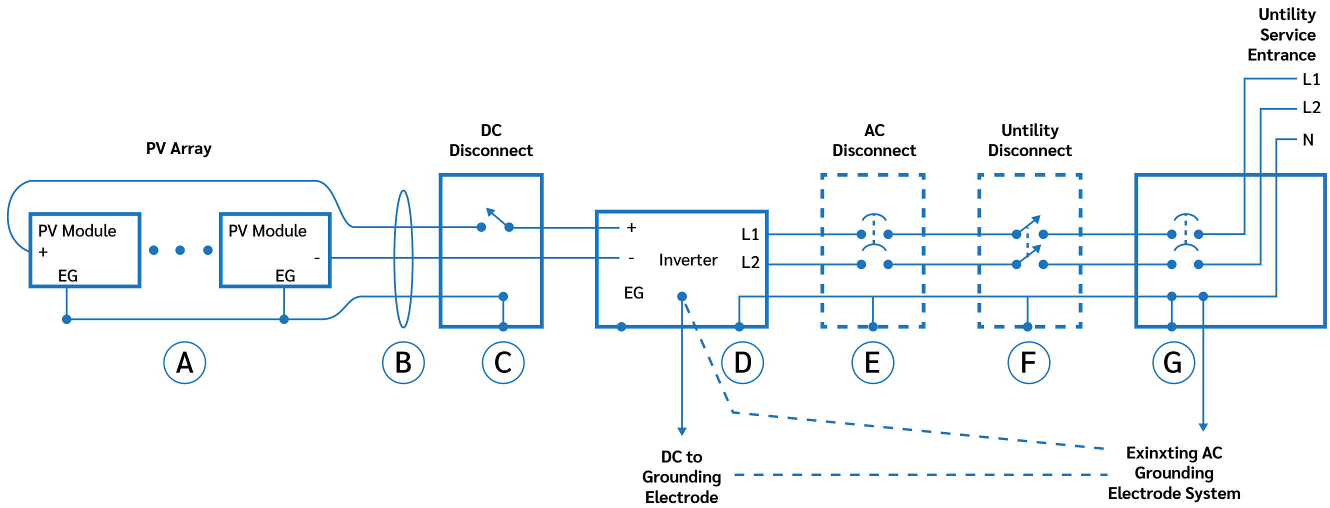


Figure 3-1 Basic Architecture of Residential PV Systems

PV Array: The core energy generation unit (A)

Modules: Individual PV modules produce DC electricity when illuminated. They have specific power, voltage, and current ratings.

Strings: Modules are typically connected in series to achieve the required system voltage (e.g., up to 600 V or even 1000-1500 V in larger systems).

Arrays: Multiple strings are often connected in parallel (usually via a combiner box) to increase the total current and power output.

Certification: Modules must meet rigorous international (IEC 61730, UL 1703) and local standards to ensure safety, reliability, and performance.

DC system components (B and C)

PV Combiners (Junction Boxes): Enclosures where multiple strings are connected in parallel. They often house overcurrent protection devices (fuses) for each string and may include monitoring equipment or disconnect switches. They must be appropriately certified.

DC Disconnects: Switches located between the PV array and the inverter (and potentially at the array) to allow for safe isolation of the DC circuits for maintenance or emergencies

Power Conversion (D)

Inverters: The heart of the PV system, converting the variable DC output from the array into grid-compliant AC power. Different inverter technologies exist:

String Inverters: Connect to one or multiple strings (most common for residential/commercial rooftops).

Microinverters: One small inverter attached to each PV module, converting DC to AC at the module level.

DC Power Optimisers: Module-level electronics that optimise the DC power output of each module before sending it to a central string inverter.

Charge Controllers: Required in systems with battery storage (stand-alone or grid-tied with backup) to regulate the charging and discharging of the batteries, protecting them from overcharging and deep discharge. Often integrated within hybrid inverters. Certification (e.g., IEC 62509, UL 1741) is crucial.

AC System Components (E)

AC Disconnects: Switches located between the inverter output and the point of connection to the building's electrical system or grid, allowing isolation of the AC side.

Utility Metering: Measures energy production and consumption/export.

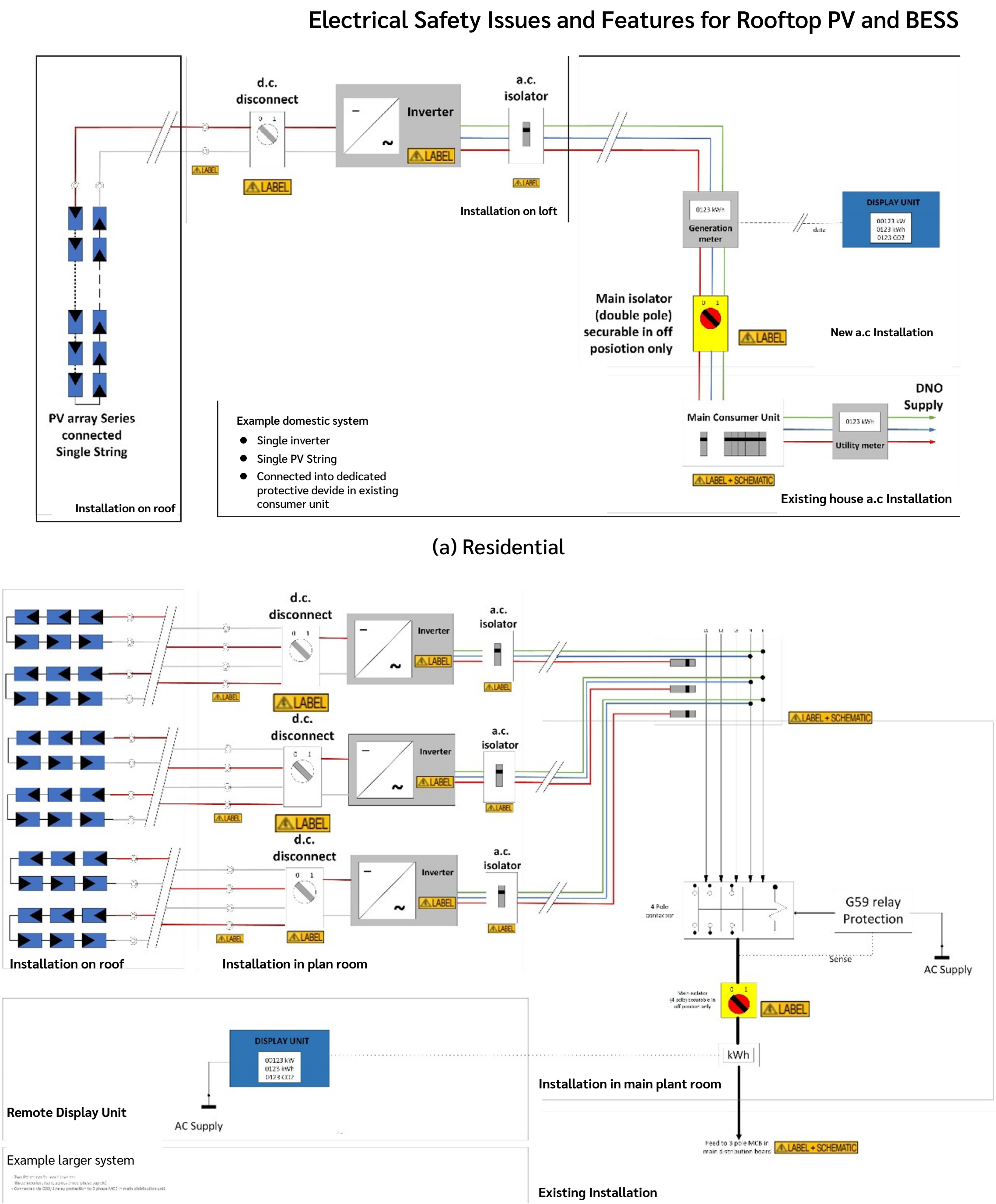
Protection Devices: Circuit breakers in the building's main panel protect the PV system's AC circuit.

Mounting and Grounding (F and G)

Mounting System: The structure securing the PV array to the roof. Must be designed to withstand environmental loads (wind, snow) and ensure proper drainage and ventilation.

Grounding System: This is essential for safety, providing a path for fault currents and protecting against electric shock and lightning surges. It involves bonding the metallic frames of modules, mounting structures, and electrical equipment enclosures to the building's grounding electrode system.

Figure 3-2 provides more detailed schematics of (a) a typical residential system with a single string array, DC disconnect, inverter, AC isolator, generation meter, and connection to the main consumer unit; and (b) a larger commercial system, potentially with multiple arrays feeding multiple inverters, DC disconnects, and AC isolators, combining protection (e.g., relay protection for grid connection), metering, and connection at a main plant room. These diagrams emphasise the required labelling and isolation points.



(a) Residential

(b) Commercial

Figure 3-2 Basic Architecture of Commercial and Industrial Rooftop Systems

Isolation Points

Residential: Shows essential isolation points: a DC disconnect near the inverter and an AC isolator near the connection point (e.g., consumer unit). These allow for basic safe isolation of the inverter and array from the building's AC system.

Commercial: Depicts multiple levels of isolation reflecting the larger system. There are DC disconnects associated with each inverter group, AC isolators for each inverter's output, and critically, a main AC isolator for the entire PV system, noted as being 'securable in off position only' (lockable). This lockable main isolator provides a crucial single point of isolation for the entire commercial PV installation, enhancing safety during major maintenance or emergencies. The presence of multiple DC and AC disconnects near the equipment allows for isolation of specific sections within the larger system.

Labelling

Both diagrams explicitly indicate the need for “LABEL” at various points, signifying the requirement for clear safety and identification markings according to standards.

Residential: Labels are shown on the DC disconnect, inverter, and AC isolator, likely indicating warnings about DC voltage, equipment identification, and operational status.

Commercial: Labelling requirements appear more extensive due to the system’s complexity. Labels are indicated on multiple DC disconnects, inverters, AC isolators, the main AC isolator, the G59 protection relay panel, and metering points. This comprehensive labelling is essential for safely navigating the more complex system, identifying different circuits, understanding protection settings, and ensuring correct operating procedures for maintenance personnel or emergency responders who may be less familiar with the specific installation.

Clear, standardised labelling at all isolation points and key components is crucial for minimising human error and ensuring personnel safety in both types of systems, but the scope is significantly larger in the commercial example.

Industrial: Industrial rooftop PV systems require enhanced safety labelling, due to their operational complexity and potentially hazardous environments. Building on general commercial labelling requirements, industrial-specific labels typically provide greater detail concerning process integration, such as interlocks with machinery and process-specific emergency shutdowns. Furthermore, these labels must exhibit harsh environmental durability, be suitable for site-specific conditions like chemicals or hazardous area classifications, and provide robust Lockout-Tagout (LOTO) support with detailed information at all isolation points.

Due to higher potential fault levels, prominent arc flash warnings detailing incident energy and required PPE are critical, alongside clear identification for specialised equipment like MV switchgear or dedicated transformers. Labelling often includes information on emergency stop systems integrated with overall plant safety protocols, all vital for ensuring safety and operational clarity in complex industrial settings.

The distinct architectures of ground-mounted and rooftop PV systems lead to different safety considerations, as summarised in Table 3-1.

Table 3-1 Comparison of Ground-mounted vs Rooftop PV Architecture

Architectural Aspect	Ground-mounted PV	Rooftop PV	Relevance to Specific Safety Considerations
Location & Proximity	On the ground, often fenced, away from the main buildings	On building roofs, integrated with the structure, close to occupants	Rooftop: Higher risk of fire spread to/from building; direct impact on occupants if structural failure occurs. Increased importance of fire-resistant materials and rapid shutdown capabilities
Accessibility	Generally, easy access for maintenance/ emergency	Requires roof access (ladders, hatches, safety harnesses)	Rooftop: Increased fall hazards during installation/ maintenance. Potentially delayed emergency response (firefighting) due to access challenges

Grounding Path	Typically, direct connection to the dedicated earth grid	Utilises the building's grounding system; potentially longer/complex paths	Rooftop: Grounding effectiveness more dependent on building infrastructure quality. Higher potential for grounding issues if not correctly installed/verified. Increases reliance on SPDs. Lack of specific rooftop grounding standards is a key concern
Lightning Exposure	Lower profile relative to surroundings	Elevated position increases exposure	Rooftop: Higher probability of direct/indirect lightning strikes. Requires robust lightning protection (SPDs) integrated with the building system (if present) and effective low-impedance grounding
Structural Integration	Independent structures designed for PV loads	Mounted on existing roof structure; load capacity must be verified	Rooftop: Risk of roof overload or damage if not properly assessed/installed. Mounting system failure poses a falling hazard. Requires careful structural design and assessment
DC Voltage Hazard	Present in both systems during daylight	Present in both systems during daylight hours	Rooftop: Hazard exists closer to occupied spaces and potentially less accessible areas. Heightens the need for Rapid Shutdown systems to de-energise the array for firefighter/maintenance safety
Environmental Factors	Exposed to ground-level conditions	Exposed to roof conditions (higher temps, wind, UV, potential water pooling)	Rooftop: Potentially faster degradation of components (cables, insulation) due to a harsher roof environment. Increased risk of water ingress/condensation issues in enclosures if not properly sealed/ventilated

3.1.2. Battery Energy Storage System

Energy can be stored through various physical and chemical processes. Mechanical methods include established technologies like pumped hydropower, which requires specific geography, as well as flywheels and compressed air energy storage, which store kinetic and potential energy, respectively. Electrical storage utilises devices like double-layer capacitors (supercapacitors) for rapid charge/discharge or superconducting magnetic energy storage. Chemical storage often involves producing hydrogen through electrolysis for later use in fuel cells. Thermal storage retains energy as heat in materials.

However, electrochemical storage, or batteries, is the most prevalent technology for grid-connected and behind-the-meter applications relevant to rooftop PV integration.

Within battery technology, various chemistries exist. Lead-acid batteries represent a mature, lower-cost option, but have limitations in energy density and cycle life. Flow batteries, which store energy in external liquid electrolytes, offer independent scaling of power and energy capacity and potentially long lifespans, though often with lower efficiency than other types. High-temperature batteries like Sodium-Sulphur (NaS) are used for long duration applications, but the adoption of this technology is still considered at an early stage.

Currently, Lithium-ion (Li-ion) chemistries dominate the stationary BESS market due to their favourable combination of high energy density, good round-trip efficiency, long cycle life, and rapidly decreasing costs.[7] Common Li-ion variants include Lithium Iron Phosphate (LFP), often preferred for stationary storage because of its enhanced safety profile and cycle durability, and chemistries like Nickel Cobalt Manganese (NCM) or

Nickel Cobalt Aluminium (NCA), which offer higher energy density. Despite their advantages, Li-ion batteries necessitate sophisticated management systems due to inherent safety risks like thermal runaway.

BESS is becoming increasingly integral, not only in stand-alone power systems, but also coupled with grid-connected RE sources like rooftop PV. Their architecture encompasses the storage technology itself, the essential management and conversion components, and the configuration defining how they connect to loads or the grid. A functional BESS integrates several crucial components:

<u>Battery Core (Cells -> Modules -> Packs -> Racks)</u>

Cells: The smallest individual electrochemical unit. Cell form factors (cylindrical, pouch, prismatic) influence cost, thermal management, mechanical robustness, and packaging density.

Modules: Cells are electrically connected (series/parallel) and mechanically assembled into modules, often including basic monitoring points.

Packs/Trays: Modules are further assembled into packs or trays, potentially incorporating module-level electronics or disconnects.

Racks/Cabinets: Multiple packs/trays are installed into racks or cabinets, which provide structural support, power/control connections, and often integrate rack-level controllers and safety devices.

<u>Battery Management System (BMS)</u>

The essential "guardian" of the battery, particularly for Li-ion. It performs multiple critical functions:

Monitoring: Continuously measures voltage, current, and temperature at the cell, module, and/or pack level using embedded sensors.

State Estimation: Calculates State-of-Charge (SOC—remaining energy) and State-of-Health (SOH—battery degradation/capacity) using algorithms (e.g., coulomb counting, voltage correlation, impedance tracking).

Protection: Prevents operation outside safe limits (over-voltage, under-voltage, over-current, over/under-temperature) by controlling contactors or alerting the PCS/EMS. Crucial for preventing thermal runaway triggers.

SOC Balancing: Actively or passively balances the charge level of individual cells within a series string to maximise usable capacity and lifespan. The active balancing is designed to receive dispatching commands from the BMS to manage energy flow between battery packs, enabling active inter-pack balancing and online charging functionality for battery packs. Each battery pack is treated as an individual energy unit, with the active balancing module's positive and negative terminals connected in parallel to the main positive and negative power lines.

During charging and discharging processes, the active balancing module can adjust the charge/discharge currents of individual battery packs. This ensures two key outcomes, namely increased total discharge capacity of the energy storage system over its entire lifecycle, and improved consistency between battery packs. Passive balancing in a BMS dissipates excess energy from higher-charged cells through resistors to equalise SOC across a battery pack. This method improves cell consistency during charging but wastes energy as heat, unlike active balancing, which redistributes energy between cells.

Communication: Reports status, data, and faults to higher-level controllers (PCS, EMS).

Battery Thermal Management System (B-TMS)

Manages the battery's operating temperature, critical for Li-ion safety, performance, and longevity. It aims to:

Dissipate Heat: Remove heat generated during charging/discharging using methods like forced air cooling, liquid cooling (more effective for dense systems), or phase-change materials.

Maintain Uniformity: Ensure minimal temperature variation across cells/modules to prevent localised stress or degradation.

Operate within Limits: Keep the battery within its specified safe operating temperature range. The B-TMS works in coordination with the BMS, which monitors temperatures and controls the thermal system's operation.

Power Conversion System (PCS)

A bidirectional inverter/converter that interfaces the DC battery with the AC grid or load. It manages the charge and discharge power flow based on commands from the EMS or BMS, ensuring AC output meets grid requirements (voltage, frequency, power quality).

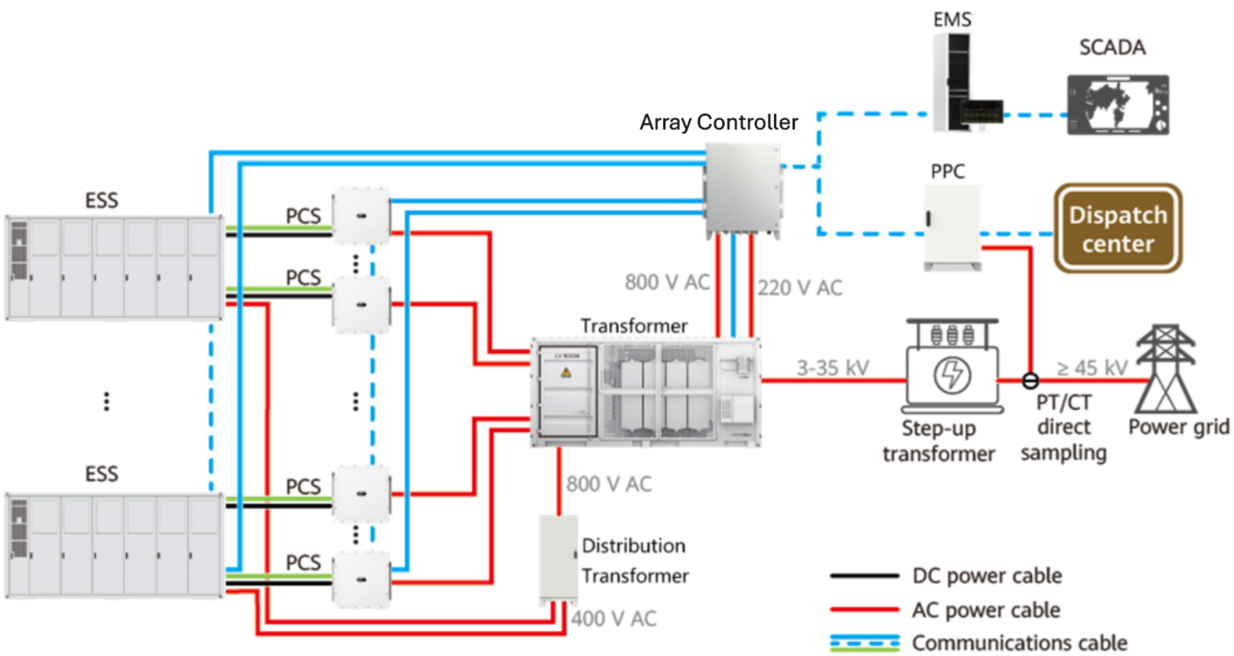
System Controller/Energy Management System (EMS)

Oversees the entire BESS operation, making decisions on when to charge or discharge based on the application (e.g., grid signals for frequency regulation, time-of-use arbitrage, maximising self-consumption from PV, providing backup power). It coordinates the PCS and BMS actions.

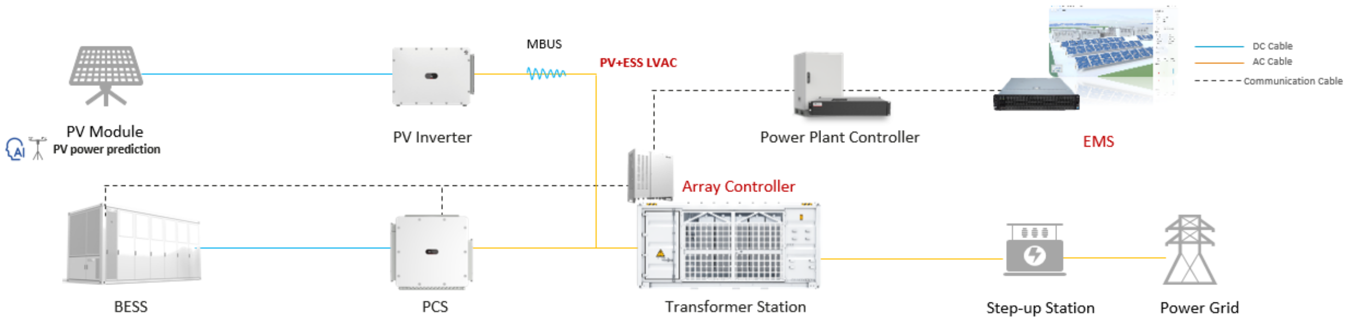
Safety & Auxiliary Systems

Includes fire detection sensors (smoke, heat, off-gas), automated fire suppression systems (e.g., clean agents, water mist), HVAC for environmental control within enclosures, main DC/AC circuit breakers and disconnects, emergency stop systems, and communication networks.

The connection configuration influences operation and protection requirements. Two primary architectures commonly used for larger BESS architectures for grid applications are demonstrated by the BESS schematic of Figure 3-3: Grid-integrated BESS and co-located with RE power generation.



(a) Grid-connected BESS



(b) BESS Co-located with RE

Figure 3-3 Basic BESS Architecture of Grid-connected and Co-located with RE Systems

3.1.3. Comparison of Grid-integrated BESS and Co-location with RE

Grid-integrated BESS

This architecture involves the BESS connecting directly to the utility grid, typically at medium or high voltage levels, via its own dedicated transformer. It is designed primarily to provide services directly supporting the stability and operation of the power grid. The configuration illustrated in Figure 33 (a) provides a representative example.

Configuration: This setup typically involves multiple containerised ESS. DC power (shown as black lines) flows from these ESS containers. In the diagram, power flows to the PCS. The PCS units convert DC power to AC power (shown as red lines). The AC power from multiple PCS units is aggregated, potentially passing through a transformer that can enable faster switching or specialised grid functions, before reaching the main step-up transformer. This transformer increases the voltage to the appropriate level for interconnection with the Power grid.

Control and Communication: A crucial element is the communication network (blue dashed lines) linking the components (ESS, PCS, transformer) to centralised control and monitoring systems. This includes a Station Controller (labelled Array Controller), which manages the plant's operation, and a plant-level monitoring system (PPC), which provides visibility and potentially interfaces with a remote dispatch centre via additional equipment (like the labelled EMS).

Applications: Primarily used for utility-scale grid services like frequency regulation, voltage support, energy arbitrage, peak shaving, providing grid reserves, or black start capabilities.

Energy Flow: Charges are made by drawing power from the grid (via the transformer and PCS operating in reverse), and discharges are made by injecting power back into the grid.

BESS Co-located with Renewable

The BESS is situated alongside a RE generation facility, such as a solar PV farm, and they share common connection infrastructure before interfacing with the main grid. This configuration primarily aims to improve the integration and value of the vRE source. The schematic shown in Figure 3-3 (b) illustrates such a setup.

Configuration: The BESS is integrated with multiple PV Farm Clusters 1-4. Each PV cluster has its own Inverter converting DC to AC. The AC output from these PV inverters, protected by circuit breakers, feeds onto a common medium voltage collection bus (yellow line). The BESS, connected via its own (implied) PCS and circuit breaker, also feeds onto this same common AC bus. The combined power from the PV clusters and the BESS on this bus is then stepped up to a higher voltage for grid export via shared transformers and associated switchgear connecting to the higher voltage grid lines (top of diagram).

Applications: Primarily used for "Renewables Firming". This allows storing excess PV energy generated during peak sun hours and discharging it later, during evening peak demand or when clouds reduce PV output to provide a smoother, more predictable power profile to the grid, meet specific grid ramp-rate requirements, or perform energy arbitrage based on PV generation patterns.

Energy Flow: Charges primarily using the excess generation from the co-located PV Farm Clusters, but could also charge from the grid if necessary. Discharges power onto the common AC bus, blending with the PV output before being exported to the grid.

The way a BESS is interconnected significantly impacts its operational characteristics, and critically, its electrical safety strategy, particularly concerning the placement and coordination of protective devices.

For the Grid-Integrated system, the primary safety focus is managing the single interface with the grid, ensuring the BESS can be safely isolated from grid faults (like short circuits) and that internal BESS faults do not adversely affect the grid. In contrast, the co-located system with RE presents a more complex safety challenge due to the shared connection point between the BESS, the renewable plant (e.g., PV), and the grid interconnection.

Protection systems must be carefully coordinated to isolate faults within any one component (BESS, PV, Grid) without causing unnecessary tripping of the others, requiring detailed system studies to prevent issues like cascading outages or failure to isolate faults effectively. These key differences are summarised in Table 3-2.

Table 3-2 Comparison of BESS Systems Grid-integrated vs Co-located with RE

Feature	Grid-integrated BESS	Co-located BESS
Primary Connection Point	Directly to Grid (via dedicated transformer)	Common AC Bus shared with Renewable Plant (then to Grid via shared transformer)
Typical Applications	Grid Services (Frequency Regulation, Voltage Support, Arbitrage, Peak Shaving, Black Start)	Renewables Firming (Smoothing Output, Energy Shifting), enhancing PV plant dispatchability
Primary Charging Source	Grid	Co-located Renewable Plant (PV) and Grid
Primary Discharge Destination	Grid	Grid (often coordinated with Renewable Plant output)

Table 3-2 Comparison of BESS Systems Grid-integrated vs Co-located with RE

Feature	Grid-integrated BESS	Co-located BESS
Safety Considerations/ Protection Focus	Focus: Isolating BESS from grid faults & vice-versa at a single interface. Grid stability support by having Active Power Unchanged during HVRT. Safety Relevance: Simpler protection coordination; primary risk is managing interaction with high grid fault levels. When high voltage transients occur on the grid, the power deviation of BESS shall not exceed 10% of the declared power under the corresponding SOC range 0–100%. In addition, no backfeed current should be allowed during the HVRT to protect BESS during operation in any of the SOC range.	Focus: Complex coordination between BESS, Renewable Plant, and Grid protection schemes. Safety Relevance: Higher risk of protection miscoordination (sympathetic tripping or failure to trip) due to multiple interacting fault sources. Fault location is more complex. Requires detailed system studies.

3.2. Safety Hazards and Mitigation

3.2.1. Rooftop PV Installations

Rooftop PV systems present a specific set of hazards due to their operating characteristics (high DC voltage), location (elevated, exposed), and component interactions. Key potential hazards include:[8], [9]

High DC Voltage and Electric Shock Risk

Hazard: PV modules generate hazardous DC voltages (typically 600-1,500 V DC) whenever exposed to sunlight, even if disconnected from the AC grid or inverter. This persistent "live" state means that installation and maintenance often involve working on or near energised circuits, posing a significant electrocution risk. Individual modules cannot simply be switched off. This risk extends to emergency responders, particularly firefighters, where the energised array can hinder suppression efforts and pose a direct shock hazard. Poor installation practices (damaged insulation, incorrect grounding) further elevate shock risks.

Mitigation: Strict adherence to safe work practices—LOTO where possible, use of insulated tools, approach boundaries—appropriate PPE, ensuring proper insulation (double/reinforced per IEC 60364-7-712). Implementing RSD systems is vital to quickly de-energise conductors within the array boundary to safe voltage levels upon initiation, protecting maintenance personnel and emergency responders. Pre-commission testing according to standards like IEC 62446-1 helps verify system integrity.

DC Arc Faults

Hazard: Arcs are luminous plasma discharges caused by current flowing through ionised air between conductors or to ground when the voltage exceeds the breakdown threshold. They produce extreme temperatures (>3,000°C), potentially igniting nearby materials. In PV systems, DC arcs are a significant fire hazard, often initiated by loose terminals, poor contacts, damaged cables, or insulation degradation. Series arcs (a break in a single conductor path) are most common (~80% of incidents). Unlike AC arcs, which naturally extinguish at zero-crossing points[1], DC arcs are sustained and more difficult to extinguish, posing a persistent fire risk. Parallel arcs—between positive and negative conductors due to insulation failure or damage—can rapidly carry higher currents and escalate fire risk.

Mitigation: High-quality installation with meticulous attention to connections (proper torque, crimping), cable management (avoiding damage, strain relief), and use of appropriate PV-rated components. The primary technical mitigation uses AFCIs, also known as Arc Fault Detection Devices (AFDD) or Protection Equipment (AFPE), designed specifically for DC PV systems. These devices detect electrical signatures characteristic of arcing and interrupt the circuit. Compliance with standards like IEC 63027 or UL 1699B is essential. The requirements are:

- **Detection length**: The conductor length refers to the bidirectional length from the PV module at the farthest end to the inverter. When performing an AFCI test, the conductor length should be simulated by the sum of inductors L4/L5 and L6/L7, as specified in clause 9.2.4 and 9.2.5 of IEC 63027, with a conductor inductance estimation of 0.75 μH/m. The actual simulated and tested conductor length should be described in the test report and consistent with the conductor length support for AFCI in the user manual or other user documentation. In any case, the tested conductor length should be ≥80 m as required by IEC 63027.
- **Detection Current**: The inverter arc detection current should cover the operating current range of the tested port. For the test method, see section 9.2.6 in IEC 63027.
- **Energy**: The energy generated by arcs should not exceed 750 J. For the test method, see section 9.2.7 in IEC 63027.
- **Time**: The time between the generation and extinguishing of an arc should not exceed 2.5s. For the test method, see section 9.2.7 in IEC 63027.
- **RSD**: RSD should be triggered after the AFCI detection is successful. The requirements for module-level RSD are:
    - Exceeding the voltage control boundary, the voltage measured between any two voltage-controlled conductors and between any voltage-controlled conductor, and the earth should not exceed 30 V within 30 seconds after RSD.
    - The PV system within the voltage control boundary should meet one of the following conditions:
        a. The PV array shall be marked as an RSD PV array. Such PV arrays shall be installed and used according to the list of RSD PV arrays, onsite labels, and the accompanying instructions.
        a. Within the voltage control boundary, the voltage measured between any two voltage-controlled conductors and between any voltage-controlled conductor and the earth should not exceed 120 V within 30 seconds after RSD.
        a. This clause does not apply to PV arrays that use unexposed voltage-controlled conductors and are more than 2.5 m away from the exposed earthing conductor or ground.
    - The trigger source for a PV rapid shutdown system can be a DC switch, AC switch, or signal switch.

1 In an AC system, the electrical current and voltage continuously change direction, oscillating in a sinusoidal waveform. A zero-crossing point is the instant in time when the AC waveform passes through zero amplitude (zero current and/or zero voltage) as it transitions from positive to negative polarity, or vice versa. This occurs twice per electrical cycle (e.g., 100 times per second for a 50 Hz system). At this point of zero current, the energy supporting an electrical arc momentarily ceases, allowing the ionised arc path to cool and de-ionise, which significantly helps the arc to extinguish naturally. DC, by contrast, maintains a constant polarity and magnitude (ideally), meaning it has no natural zero-crossing points. This continuous current flow makes it much harder for DC arcs to self-extinguish once initiated.

- If the system solution supports AFCI, RSD can be triggered after the AFCI detection is successful.
- The ambient temperature ranges from –40°C to +85°C.

Challenges in DC Arc Detection

Accurate DC arc detection remains challenging. While AC AFCI technology is mature, leveraging zero-crossings and distinct AC waveform characteristics, DC arcs lack these features.[10],[11] DC arc waveforms can resemble normal operating noise, especially fluctuating inverter noise. Key challenges include:

- **Noise Adaptability**: It is difficult to distinguish true arc signatures from background electrical noise generated by inverters or external sources. Environmental noise spectra might overlap with arc spectra, leading to false trips or missed detections, especially with complex arc types (parallel, ground).
- **Scenario Adaptability**: As PV systems evolve with higher module currents and longer cable runs, the characteristic high-frequency arc signal weakens and becomes harder to reliably detect over distance and against higher baseline currents, requiring more sensitive and intelligent detection algorithms.

Balancing detection sensitivity (catching real arcs) with immunity to nuisance tripping remains a key challenge for commercial DC AFCI products. To improve performance, advanced algorithms, sometimes employing AI/machine learning, are being developed.

Other Fire Hazards (Non-Arc Related)

Hazard: Undetected fault currents, even if not arcing, can cause overheating and lead to fires. Poor electrical contacts (DC or AC terminals) due to improper crimping/tightening or loosening over time (vibration, thermal cycling) create high resistance points that overheat, potentially melting insulation and igniting adjacent materials. Internal inverter component failures (capacitors, insulated gate bipolar transistors or IGBTs) can also lead to overheating or short circuits.

Mitigation: Adherence to good DC system design principles, careful installation practices (correct torque specifications, proper crimping), use of quality components, thermal inspections during commissioning and maintenance, and appropriate overcurrent protection design.

DC Overcurrent Protection Limitations

Hazard: Effectively protecting DC circuits with fuses or circuit breakers is challenging. Unlike AC systems, the DC short-circuit current from a PV string is often only slightly higher (~1.1 times) than the normal maximum operating current. Standard fuses may struggle to reliably and quickly interrupt these low-level overcurrents, potentially allowing fault conditions to persist. Furthermore, many traditional string inverters lack the ability to actively disconnect the DC input, meaning internal inverter short circuits cannot be isolated from the array, increasing fire propagation risk.

Mitigation: Careful selection of DC fuses specifically rated for PV applications (gPV type conforming to IEC 60269-6), proper coordination based on system parameters, use of inverters with integrated DC isolation capabilities, and adherence to design guidelines (e.g., IEC 62548).

Grounding Faults

Hazard: While a single DC ground fault (connection between a current-carrying conductor and ground) might not cause large currents immediately in some system types (e.g., ungrounded, or functionally grounded), it compromises safety. Simultaneous faults (e.g., positive-to-ground on one string, negative-to-ground on another) can lead to significant fault currents, hazardous voltages potentially double the system voltage, or internal inverter damage if interacting with AC grounding. Locating intermittent or high-resistance ground faults can be difficult, especially in large systems.

Mitigation: Implementing robust equipment grounding and bonding according to standards (e.g., IEC 60364 series). Utilising Ground Fault Detection and Interruption (GFDI) devices, or Insulation Monitoring Devices (IMDS) as required by standards (e.g., IEC 60364-7-712) to detect current leakage and trigger alarms or shutdown. Performing periodic insulation resistance tests to identify degradation before failure.

Electrical Insulation Failure

Hazard: Insulation on cables, connectors, and internal components degrades over time due to environmental stresses common on rooftops: UV radiation, high temperatures, thermal cycling, moisture ingress (including condensation inside enclosures even with high IP ratings), and mechanical stress. Degraded insulation can lead to current leakage, ground faults, short circuits, arcing, and electric shock hazards. Condensation within inverter or combiner enclosures is a noted cause of insulation breakdown. Other common causes include loose MC4 connectors (connecting one PV modules to the other).

Mitigation: Selecting cables and components with appropriate ratings for voltage, temperature, and UV resistance suitable for the outdoor rooftop environment. Use proper installation techniques (e.g., conduit, strain relief, avoiding sharp edges) to prevent mechanical damage. Ensuring enclosure integrity (IP rating) and potentially using breathable vents to manage condensation. Conducting periodic visual inspections and insulation resistance testing.

Installation Quality and Wiring Practices

Hazard: Poor wiring design or installation practices that do not follow standards significantly increase the risk of faults and electrical shock for installers, operators, maintenance personnel, and building occupants. Examples include incorrect polarity connections, inadequate conductor sizing, poor cable management leading to damage, and improper use of connectors.

DC Reverse Connection: Incorrectly connecting positive and negative DC connectors during installation is a specific risk, especially with numerous connections. Reversing one string in a parallel set can impose double the voltage across protection devices (e.g., fuses), potentially causing them to fail violently under fault conditions. Reversing all strings into an Maximum Power Point Tracking (MPPT) inverter can damage internal components.

Mitigation: Employ qualified and trained installers. Adhere strictly to relevant installation standards (e.g., IEC 60364-7-712, IEC 62548) and manufacturer instructions. Use appropriate tools (e.g., torque wrenches). Implement quality control checks during installation, including polarity tests before connection. Utilise keyed connectors designed to prevent reverse polarity mating.

Mounting System Failures & Structural Hazards

Hazard: Inadequate design or improper installation of the mounting system can lead to rack structural failure or roof structure overloading. Failures can be caused by underestimating wind/snow loads, corrosion, thermal expansion stress, or installation errors. This can result in detached panels, posing both a falling hazard and severe electrical risks (damaged wiring, short circuits).

Mitigation: Conduct a thorough structural assessment of the roof before installation. Use certified mounting systems designed and tested for relevant environmental loads. Follow the manufacturer’s installation instructions precisely. Use corrosion-resistant materials appropriate for the environment. Regularly inspect the mounting system integrity.

Combination of Hazards on Rooftops

Hazard: Rooftop PV work presents a unique convergence of multiple hazards simultaneously: risk of electric shock from live DC components, risk of falling from height, and manual handling difficulties with large/awkward panels. Personnel may be experts in one area, but not others (e.g., electricians unused to height safety, roofers unused to electrical hazards).

Mitigation: Comprehensive site-specific risk assessments and safety planning covering all potential hazards. Use of appropriate fall protection equipment. Proper manual handling training and techniques. Ensuring workers have adequate cross-disciplinary safety awareness and work in supervised teams with complementary skills.

Inverter Internal Fault Propagation

Hazard: Failures within the inverter itself (e.g., power electronic components like capacitors or IGBTs) can lead to internal DC bus short circuits. While AC-side protection might operate, if the inverter lacks internal DC isolation capability (common in older or simpler string inverters), the fault can persist, fed by the PV array. If the fault causes a breakdown between the AC and DC sides, the AC grid power could potentially backfeed into the DC side, leading to severe inverter damage and/or fire.

Mitigation: Utilising inverters certified to safety standards (IEC 62109), which include requirements for internal fault protection. Preferring inverter designs that incorporate DC-side fault interruption or isolation mechanisms.

Arcing in Associated AC Switchgear (Larger Systems)

Hazard: For larger systems connecting via dedicated transformer stations, faults can occur in the low-voltage AC cabinets. Operation of large circuit breakers (MCCBs) during high short-circuit currents can eject hot, ionised particles. If these land on exposed busbars or terminals, they can trigger secondary phase-to-phase or phase-to-ground faults (arcing), leading to severe cabinet damage, explosion, or fire.

Mitigation: Utilising switchgear compliant with relevant standards (e.g., IEC 61439) that incorporates designs to manage internal arcing faults (arc-resistant switchgear) or prevent particle contamination of live parts. Implementing proper maintenance and cleaning schedules for switchgear.

Having examined the specific details of potential hazards inherent in rooftop PV systems, from persistent DC voltage risks to complex arc fault phenomena and installation challenges, Table 3-3 offers a high-level overview. It summarises the essential characteristics and corresponding primary mitigation strategies for each major hazard discussed, intended as a quick reference guide.

Table 3-3 Rooftop PV Hazards and Mitigation Measures

Potential Hazard	Key Characteristics/Risks	Primary Mitigation Measures
High DC Voltage/ Electric Shock Risk	Persistent live DC voltage (600-1,500 V+) during daylight, risk to installers/maintenance/ firefighters.	RSD systems, Safe Work Practices (LOTO, insulated tools, PPE), Double/Reinforced Insulation (IEC 60364-7-712).
DC Arc Faults (Series & Parallel)	Sustained high-temperature plasma discharge due to faults; difficult to extinguish; major fire risk.	DC Arc Fault Circuit Interrupters (AFCI/AFPE - IEC 63027, UL 1699B), High-Quality Installation (connections, cable management).

Other Fire Hazards (Non-Arc)	Overheating from high resistance (poor contacts), component failures leading to ignition.	Proper installation (torque, crimping), quality components, thermal inspections, and good system design are required.
DC Overcurrent Protection Limitations	Low DC fault currents (~1.1x operating current) difficult for standard fuses/breakers to clear reliably.	PV-rated Fuses (IEC 60269-6), Careful Protection Coordination, Inverters with DC Isolation Capability.
Grounding Faults	Leakage current to ground; multiple faults can cause high currents or overvoltages.	Robust Grounding/Bonding (IEC 60364), GFDI or IMD, Periodic Testing.
Electrical Insulation Failure	Degradation from UV, heat, moisture (condensation), stress leads to shorts, arcs, and shock risk.	Properly Rated Materials (UV/Temp), Proper Installation (strain relief), Enclosure Integrity (IP rating, vents), Periodic Testing.
Installation Quality/Wiring Practices	Non-standard work increases fault/shock risk (e.g., poor connections, damaged cables).	Qualified Installers, Adherence to Standards (IEC 60364-7-712, IEC 62548), Quality Control Checks.
DC Reverse Connection	WIncorrect polarity connection during installation; risks overvoltage on protection, component damage.	Careful Procedures, Polarity Checks, Keyed Connectors, Component Robustness.
Mounting System Failures	Structural failure from load, corrosion, poor installation; risk of falling panels & electrical hazards.	Structural Assessment, Certified Mounting Systems, Correct Installation, Corrosion Protection, Inspections.
Combination Hazard (Shock, Fall, Handling)	Simultaneous risks of electrical shock, falls from height, and difficult manual handling on rooftops.	Integrated Safety Planning, Fall Protection, Proper Manual Handling Training/Techniques, Cross-Disciplinary Awareness.
Inverter Internal Fault Propagation	Internal inverter failure escalates due to lack of DC isolation, potential AC backfeed.	Inverter Safety Standards (IEC 62109), Designs with DC Isolation/Fault Interruption.
Arcing in Associated AC Switchgear	Ejected particles from AC breaker operation cause secondary arcing faults in LV cabinets (larger systems).	Arc-Resistant Switchgear Design (IEC 61439), Proper Maintenance.

3.2.2. BESS Installations

BESS, particularly those utilising Li-ion chemistries, present unique and significant safety challenges that must be managed throughout their operational lifecycle. These challenges arise from diverse risk sources, which if not adequately addressed through robust design, installation, operation, and mitigation strategies, can escalate into critical failures involving fire or explosion. The primary sources of risk contributing to BESS safety incidents can be broadly categorised as: [12]

- **Non-battery risks**: Hazards originating external to the battery system itself, such as electrical short circuits or arcing in connected equipment, or exposure of the BESS unit to external open flames.
- **External risks**: Environmental or mechanical stressors acting upon the BESS, including physical impacts (drops, vibration during transport), or environmental conditions like condensation and moisture ingress.
- **Electrical risks**: Issues within the BESS electrical circuits, such as insulation failures, damaging overvoltage events, or overcurrent conditions that exceed design limits, compromising system integrity.

- **Internal defects**: Flaws originating within the battery cells or modules, often due to manufacturing imperfections like electrode burrs, inconsistent coatings, defective bonding, contaminants, or the formation of lithium plating during operation, which can lead to internal short circuits and thermal instability.
- **Control failures**: Malfunctions in the monitoring and control systems, including inaccurate sensor readings (sampling errors), communication breakdowns between components, or faults within the BMS logic, prevent timely detection and mitigation of hazardous conditions.

If these initiating risks are not adequately mitigated, they can trigger a dangerous sequence of events, often referred to as the BESS failure path.

- **Sharp Temperature Rise/Open Valve**: An initial fault leads to rapid localised heating within a cell, potentially causing the cell's safety vent to open.
- **Thermal Runaway**: The cell enters a self-sustaining exothermic chemical reaction, rapidly increasing temperature and pressure.
- **Thermal Runaway Diffusion**: Intense heat spreads to adjacent cells, potentially triggering a cascading failure.
- **Violent Explosion/Fire**: Escalating thermal runaway generates flammable gases, increases pressure, and often results in fire and/or explosion.

Li-ion batteries are particularly susceptible to certain hazards, as detailed in Table 3-4. In particular, thermal runaway in Li-ion cells occurs when internal heat generation vastly exceeds heat dissipation. Key initiating factors (Failure Causes) include external high temperatures, electrical abuse, internal defects, external short circuits, and mechanical abuse. These causes often progress through a typical process: (1) Intermediate Failure State (internal short, temperature rise, separator melt); and (2) Safety Failure Stage (accelerating temperature rise, venting, thermal diffusion, fire/explosion).[13]

Table 3-4 Potential Hazards of Li-ion BESS

Hazards	Specific Aspect	Description
Thermal Runaway	*Self-Heating Chain Reaction*	Overheating triggers a self-sustaining reaction leading to extreme heat, fire, and explosion
	Difficult to Extinguish	Li-ion fires burn intensely and are hard to extinguish with conventional agents
Overcharging and Over-Discharging	*Overcharging*	Excess voltage causes lithium plating, increasing short circuit risk
	Over-Discharging	Discharging below safe voltage damages components, causing instability
Internal Short Circuit	*Separator Failure*	Damage to the separator allows electrode contact, causing rapid discharge and heat
Sensitivity to Physical Damage	*Crushing or Puncturing*	Mechanical abuse compromises internal structure, potentially causing shorts, leaks, fire
	Swelling & Gas Buildup	Damage or internal reactions release gases, causing swelling and potential rupture
Chemical Instability	*Toxic/Flammable Electrolytes*	Electrolytes are flammable and can release toxic gases upon heating or leakage
	Exothermic Reactions/Oxygen	Cathode decomposition at high temperatures can release oxygen, intensifying fire

Due to these inherent risks, Li-ion BESS necessitates strict adherence to safety standards and careful handling. Table 3-5 outlines mitigation measures across different system levels and components, e.g., the battery cells, management systems (BMS, B-TMS), and overall system design to enhance safety and reliability.

Table 3-5 BESS Electrical Safety Components

BESS Components	Roles	Functions
BMS	*Critical Role*	Regulates charge/discharge to prevent over/under voltage; monitors cell voltage/temperature via sensors for real-time control & fault detection; calculates SOC/SOH to track health/degradation; performs cell balancing; executes advanced fault detection (overcurrent, shorts, thermal imbalance) triggering alarms/protective actions (e.g., opening contactors for isolation); must comply with safety standards (IEC 62619, UL 1973) for functional safety and reliability.
B-TMS	*Function*	Dissipates heat, maintains optimal/uniform battery temperature using air/liquid cooling to prevent thermal runaway initiation and slow propagation; crucial for Li-ion safety and lifespan. Validation: System-level thermal runaway propagation testing (e.g., UL 9540A) is vital to verify the effectiveness of the B-TMS and overall system design (containment, venting, suppression) in preventing cell-to-cell or module-to-module spread.
Protective Casings	*Reinforcement*	Robust enclosures for cells, modules, and systems help mitigate the impact of external physical damage (impacts, crushing). Some market practices with high temperature zinc-based steel enclosure with Mica sheets are able to withstand high temperature with melting points above 1,500°C
Safe Charging Practices	*Maintenance*	Utilising certified charging equipment (PCS) and adhering to manufacturer-specified operating conditions (especially avoiding extreme temperatures) helps prevent electrical abuse and prolong battery life.
Combustible Gas Sensors	*Early Warning*	Detect accumulation of flammable gases (e.g., H2, CO, electrolyte vapours) released in the early stages of cell venting/thermal runaway.
	Action	Trigger early alarms/countermeasures (ventilation, shutdown, suppression) below Lower Flammable Limit (LFL) concentrations. Integration with BMS and fire suppression systems is recommended.
Active safety-Overtemperature protection of power connection terminals	*Detection*	Temperature detection and overtemperature protection measures are provided to prevent fire risks caused by loose connections at power terminals
Active safety-Online insulation monitoring	*Monitoring*	An ESS array (ESS sub-system) supports online insulation monitoring. It can automatically locate and disconnect a faulty rack.
Fire Detection & Suppression	*Detection*	Uses smoke, heat, and/or gas sensors. Suppression: Automatically activates agents (clean agents, water mist, aerosols). System design must comply with standards like NFPA 855

Directional Smoke Duct & Pressure Relief Valve	*Exhaust Gases*	The container is recommended to equip with directional smoke exhaust ducts that match the battery packs. A rebound explosion-proof pressure relief valve is installed on a well-sealed battery pack. When gases are generated due to thermal runaway, combustible gases are directed to the specified smoke duct only through the explosion-proof valve to prevent the smoke from spreading outside the battery pack. After the exhaust is complete, the explosion-proof valve rebounds to prevent oxygen from entering the pack. The exhaust fans are started to control the combustible gas concentration below the LEL of 25%.
Deflagration/ Explosion Venting	*Pressure Relief*	The ESS should have the deflagration venting function (for example, using deflagration venting panel). If an explosion occurs in the cabinet, the pressure should be relieved immediately. During deflagration venting testing, the enclosure should not break down, no metal parts of the system are ejected outside, and the pressure wave and heat radiation at a measurement distance of 3m must not cause personal injury. Prevents catastrophic enclosure rupture during thermal runaway by safely venting pressure and gases via engineered vents. Compliance: Design must follow standards like NFPA 68 and NFPA 855, informed by UL 9540A tests.

Beyond the general measures listed in the table, specific design features aim to prevent the initiation or mitigate the propagation of failures:

- Cell-Level Features:
  - *Advanced Separators*: e.g., Ceramic coated for better thermal stability and puncture resistance.
  - *Intelligent Internal Short Circuit Detection*: Algorithms for rapid detection based on voltage/current monitoring.[14]
- **Pack-Level Features**:
  - *Robust Mechanical Design/Testing*: High-strength structures validated by tests (e.g., drop tests).
- **System-Level Features**:
  - *Compartment Isolation*: Physically separated compartments within enclosures for batteries, controls, safety systems to contain faults. High IP ratings and corrosion resistance enhance durability.
  - *Multi-level Electrical Protection*: Hierarchical strategy with proactive (BMS/controller shutdowns) and passive (fuses, breakers) protection at multiple levels.

Understanding the linkage between specific BESS hazards and the available mitigation strategies, Table 3-6 summarises the primary mitigation measures associated with the key potential hazards identified for BESS installations.

Table 3-6 BESS Hazards and Corresponding Mitigation Measures

Potential Hazards	Primary Mitigation Measures
Thermal Runaway	BMS (Protection, Monitoring), B-TMS (Cooling, Uniformity), Gas Sensors (Early Detection), Fire Detection & Suppression, Deflagration Venting, Advanced Cell Separators, System Compartment Isolation, Quality Manufacturing
Overcharging	BMS (Voltage Control, Protection Limits), Safe Charging Practices (Certified PCS)
Over-Discharging	BMS (Voltage Control, Protection Limits)
Internal Short Circuit	Quality Manufacturing Control, Advanced Cell Separators, BMS (Monitoring, Detection Algorithms), Cell-Level Internal Short Circuit Detection
External Short Circuit	Multi-Level Electrical Protection (Fuses, Breakers, Contactors), Proper Installation (Insulation, Wiring), Enclosure Integrity (IP Rating)
Physical Damage (Crush/Puncture)	Protective Casings/Enclosures, Robust Mechanical Design & Testing (Pack Level), Careful Handling & Transport Procedures
Swelling/Gas Buildup/ Venting	Cell Safety Vents, Deflagration/Explosion Venting (System Level), BMS (Monitoring for precursors), Gas Sensors
Chemical Hazards (Leakage/Toxic Gas)	Containment Design, Enclosure Ventilation, Gas Sensors, Chemical-Resistant Materials, PPE during Maintenance
Chemical Hazards (Flammable Electrolyte/Oxygen Release)	Fire Suppression Systems (appropriate agents), Deflagration Venting, BMS/B-TMS (Preventing trigger conditions like overheating)
Control System Failures (BMS, Sensors etc.)	High-Reliability Component Design, Software Validation, Redundancy (where applicable), Thorough Commissioning & System Integration Testing
Environmental Hazards (Water Ingress etc.)	High IP Rated Enclosures, Proper Installation Seals, Condensation Management (Vents/ HVAC), Site Selection

3.3. Case Studies of Safety Incidents

Analysing real-world safety incidents involving PV and BESS installations provides critical context and reinforces the importance of addressing previously discussed hazards. Although detailed statistics on solar rooftop and battery accidents in ASEAN are yet to be available, the following case studies are compiled based on publicly available information and reports. They are intended to illustrate common issues and do not necessarily reflect the complete statistics or total number of safety incidents occurring within the ASEAN region or globally.

3.3.1. ASEAN Examples

These ASEAN examples consistently illustrate that safety incidents often stem from a combination of factors, including inadequate design considerations (lack of RSD, improper grounding/SPDs), poor installation quality or lack of expertise, component issues, insufficient site assessment, such as proximity to hazards like power lines), and sometimes external factors interacting with system vulnerabilities.

Indonesia

Residential Fire after Lightning Strike (Seimanggaris, North Kalimantan – April 2025): A two-story house fire reportedly occurred after a lightning strike hit the rooftop PV system. The incident resulted in substantial material loss, but no reported injuries. Preliminary information indicated a lack of adequate lightning protection and grounding infrastructure, which is especially critical in Indonesia's high-thunderstorm frequency zones. The absence of appropriate SPDs likely contributed to the severity of the incident.[15]

Possible Root Causes: Lightning/Overvoltage Event, Inadequate Grounding/SPDs, Environmental Factors (Lightning).

Malaysia

Mydin Mall Rooftop PV Fire Spread (Manjoi - March 2024): A fire that started in the supermarket's switch room spread upwards to the rooftop PV installation. Firefighting efforts were complicated by the PV system remaining energised due to the absence of an RSD system, posing electrical hazards. Access difficulties also hampered responders. This significant incident prompted Malaysia's Fire and Rescue Department (Bomba) to announce the development of new, specific fire safety guidelines for rooftop PV installations, emphasising features like fire lanes and integrated shutdown capabilities.[9]

Possible Root Causes: Fire Propagation (External to PV), Lack of RSD, High DC Voltage Hazard (during emergency), Installation Design (Firefighting Access).

Installer Electrocutions (Ranau, Sabah - December 2024): Three contract workers (one local aged 54, two foreign nationals aged 25 and 36) died from electrocution while installing solar panels on a Public Works Department building. Working on metal scaffolding at a height of approximately 7.3 m, a panel they were handling contacted an adjacent 11 kV overhead power line. A fourth worker on the ground was unharmed. This tragic incident prompted industry associations like Malaysian Photovoltaic Industry Association (MPIA) to reiterate calls for stringent safety protocols, hazard assessment (especially proximity to power lines), and proper training for installers.[16]

Possible Root Causes: Electric Shock Risk (External High-Voltage Contact), Installation Hazard (Working near energised lines, inadequate site assessment/safety planning), Combination Hazard (Height, Manual Handling, Electrical), and Lack of Expertise/Knowledge.

Myanmar

Household solar rooftop causes fire (Bago Region – May 2019): overheated solar panels linked to a residential battery in Nyaungbintha village triggered the blaze.

Possible Root Causes: Installation Hazard (Working near energised lines, inadequate site assessment/safety planning).

Philippines

Installation Electrocution Injury (Bacolod City - February 2025): Six workers were injured, suffering burns from electrocution while installing solar panels on a road's centre island. A backhoe near the worksite reportedly snagged an electric post, causing contact between the installed solar equipment and a live power line.[17]

Possible Root Causes: Electric Shock Risk (External High-Voltage Contact) and installation Hazards (Use of machinery near power lines, inadequate site coordination/safety).

Installation Electrocution Fatality (Cagayan de Oro - March 2025): A 32-year-old man died after being electrocuted while installing solar streetlights. He and fellow workers accidentally made contact with a live power line during the installation process. This involved streetlights, not rooftop PV, but it illustrates similar risks associated with installation near energised lines.

Possible Root Causes: Electric Shock Risk (External High Voltage Contact), Installation Hazard (Working near energised lines).

Singapore

Factory Rooftop PV Fire (August 2024): A fire occurred within a 15 m x 10 m section of solar panels mounted on the zinc roof of a single-storey factory at 11 Kian Teck Road. The fire spread quickly across the panels, but was extinguished within 20 minutes by fire fighters after 76 workers were evacuated safely. Preliminary findings indicated an electrical fault within the PV system itself as the likely cause. Possible root causes mentioned include improper installation (e.g., poor crimping, loose connections, faulty connectors) or the use of inferior components leading to electrical arcing and ignition.[18]

Possible Root Causes: DC Arc Faults, Installation Quality Issues, Component Failure (Substandard Components), Contact Faults, Insulation Failure.

Worker Electrocution during Installation (June 2024): An installation worker noticed an exposed PV cable arcing and emitting smoke while working on a rooftop that was wet from prior rain. Upon making contact with the cable, the worker suffered a fatal electric shock. Investigations suggested the system lacked RSD capabilities, leaving the high DC voltage conductors energised under hazardous, conductive conditions. The Workplace Safety and Health (WSH) Council highlighted electrocution as a major concern and recommended measures like insulating exposed parts and stopping work in bad weather.[19]

Possible Root Causes: Electric Shock Risk (during installation), Insulation Failure, DC Arc Faults, Lack of RSD, Environmental Factors (Wet conditions), and Combination Hazards.

Thailand

Telecom Centre Fire & Firefighter Injury (March 2022): A fire incident at a telecom centre with rooftop PV was exacerbated by the lack of RSD. The continuously energised PV array hindered firefighting, leading to a firefighter receiving electrical burns.[9]

Possible Root Causes: Lack of RSD, High DC Voltage Hazard (during emergency), Electric Shock Risk (to responders).

Household solar rooftop fire (Bangkok - January 2024): A detached house equipped with 2-year-old solar rooftop and battery was ignited by an electrical arc and battery explosion during daylight hours, resulting in one fatality.

Possible Root Causes: DC Arc Faults, Installation Quality Issues, Component Failure.

Viet Nam

Solar Panel Storage Fire (January 2018): A large cache of 34,000 new solar panels was destroyed by fire while in storage. The fire is suspected to have originated from external garbage burning that spread to the storage area. This points to potential deficiencies in site management and the lack of fire safety measures for stored materials, such as inadequate spacing, absence of fire breaks, or use of flammable packing materials, rather than an operational system failure.[20]

Possible Root Causes: External Fire Exposure, Site Management Practices (Inadequate Fire Safety Planning for Storage).

3.3.2. Global Cases

In the global context, a primary cluster of issues relates to installation quality and component integrity. For rooftop PV, this frequently manifests as poor workmanship in electrical connections (improper crimping, loose terminals, mismatched connectors) leading to overheating or DC arcing, faulty DC isolators (especially due to environmental degradation or improper sealing), inadequate grounding, and substandard components. For BESS, manufacturing defects within battery cells (e.g., electrode inconsistencies, separator flaws) are significant internal risk factors, while component failures like cooling system leaks or faulty control sensors can trigger failures.

Beyond component and installation quality, system design deficiencies and integration challenges are also major contributors. In PV systems, the lack of essential safety layers like RSD capabilities or effective DC AFCIs, along with insufficient lightning/surge protection, are recurrent themes in incidents with severe consequences. For BESS, inadequate thermal management system design, poor system integration (especially in multi-vendor projects, leading to compatibility or control conflicts), lack of robust fire suppression and venting, and insufficient commissioning validation contribute significantly to risk. Operational factors like control system malfunctions (e.g., BMS errors), lack of condition monitoring, insufficient maintenance, and external events like physical damage during transport or extreme weather also contribute to initiating or exacerbating incidents around the globe.

Australia

Victorian Big Battery Fire (Geelong, Victoria - July 2021): During initial testing/ commissioning of Tesla Megapacks for this 300 MW/450 MWh BESS project, a fire ignited within one containerised unit and spread to a second. The likely root cause was identified as a leak in the liquid cooling system (B-TMS), leading to arcing and subsequent thermal runaway in the Li-ion batteries. The fire burned for several days.[21]

Possible Root Causes: Component Failure (Cooling System Leak), Electrical Risk (Arcing), Thermal Runaway, Thermal Management Failure, Commissioning Phase Incident.

DC Isolator-Related Rooftop PV Fires (Nationwide Trend - 2022-2023): Multiple Australian states reported sharp increases in rooftop solar fires specifically linked to faulty DC isolators located on the roof near the panels. For example, Victoria saw 27 such fires in 2022-2023 (up from 15), Northern Territory had 11 (up from 4), Queensland had 11, and Western Australia had 14. Australia previously mandated these rooftop isolators (unlike most countries), but the requirement was removed in late 2021/mid-2022, due to safety concerns. Failures are often attributed to water ingress from improper sealing or installation, leading to corrosion, short circuits, or arcing. Lack of regular maintenance on aging systems is also a factor.[22],[23]

Possible Root Causes: Component Failure (DC Isolator), Installation Quality Issues (Improper Sealing), Environmental Factors (Water Ingress, Degradation), DC Arc Faults, Lack of Maintenance.

Factory Roof Fire After Hail Damage (Moorebank, New South Wales - Post-2020 Storm): Following a severe hailstorm that damaged rooftop solar panels on a factory roof, a fire reportedly broke out three days later during sunny conditions. The damaged panels were suspected of developing faults (potentially internal shorts or damaged connections) that led to arcing and igniting roofing materials.[24]

Possible Root Causes: Mechanical Damage (Hail), Component Failure (Panel Internal Fault), DC Arc Faults, Environmental Factors (Weather Damage).

Sydney Olympic Park Aquatic Centre PV Fire (Sydney, New South Wales - May 2024): A fire occurred involving the rooftop solar system at this major public facility, prompting evacuation. The incident highlighted challenges for firefighters dealing with energised panels and led to calls for mandatory RSD systems in Australia, which are not currently required nationwide. The specific cause of the fire was under investigation.[25]

Possible Root Causes: Under Investigation - Emphasises Lack of RSD as a contributing factor to response difficulty.

Belgium

School Rooftop PV Fire (Halle - April 2025): A fire damaged about 100 panels of a 160-panel PV system on a school roof. It was quickly controlled with no injuries. A technical defect within one of the solar panels was suspected as the initiating cause. The fire produced significant smoke, possibly exacerbated by roofing materials underneath.[26]

Possible Root Causes: Component Failure (PV Module Internal Fault), potential Fire Propagation involving roofing materials.

China [13]

Zhuhai Guangtong Logistics Park BESS Fire (August 2023): An ESS failure resulting in fire was attributed to uneven copper foil coating on the positive electrode during battery cell manufacturing. This internal defect led directly to battery thermal runaway.

Possible Root Causes: Internal Defect (Manufacturing Flaw), Thermal Runaway.

Yinchuan, Ningxia BESS Fire (Aug 2023): A fire incident was reportedly caused by improper cell temperature data collection, which led to uncontrolled operation and overheating of high-power cells during charging. Potential 'tip discharge' issues specific to the blade battery shape were also implicated as causing sparks.

Possible Root Causes: Control Failure (Incorrect Temperature Data/Logic), Electrical Abuse (Overheating during charge), Internal Defect (potential design issue - tip discharge).

Changshu, Jiangsu BESS Fire (May 2023): An insufficient injection moulding process during manufacturing allegedly caused deformation in a cell's plastic top cover frame. This resulted in insulation failure and an internal short circuit between the negative lug and the positive aluminium shell, leading to thermal failure, venting, and fire propagation.

Possible Root Causes: Internal Defect (Manufacturing Flaw - moulding/insulation), Insulation Failure, Internal Short Circuit, Thermal Runaway.

Expressway Transport BESS Fire (March 2023): A fire occurred while transporting BESS modules. Non-standard procedures and violent vibration reportedly caused batteries to dislodge, breaking insulation plates. An external short circuit occurred when electrodes contacted current-transmitting bars, resulting in thermal runaway and fire.

Possible Root Causes: External Risk (Vibration/Shock during Transport), Mechanical Damage, Insulation Failure, External Short Circuit, Thermal Runaway.

Hainan Yingge Salt Farm BESS Fire (Oct 2022): A fire reportedly started due to unprofessional commissioning of secondary UPS equipment. Suspected incorrect phase sequence wiring led to a short circuit on a primary bus line, igniting the bus cabinet and spreading the fire to the battery compartment.

Possible Root Causes: Commissioning Error, Electrical Risk (Short Circuit - auxiliary equipment related), Fire Propagation.

Subei County, Gansu BESS Incident (March 2024): An incident occurred at a BESS site involving components from multiple vendors (‘patchwork’ solution). Suspected causes included compatibility risks and insufficient joint commissioning between the different EMS, PCS, and battery systems suppliers.

Possible Root Causes: System Integration Risk (Compatibility Issues), Commissioning Error, Control Failure.

Germany [27]

Warehouse Rooftop PV Fire (Goch - 2012): A fire occurred at a warehouse, involving a large (approx. 4,000 m^2) rooftop PV system. The fire’s cause was reportedly linked to a defect within the PV system components. Images associated with analysis of such fires often point to failed connectors or DC isolators as potential ignition points.

Possible Root Causes: Component Failure (Isolator/Connector), DC Arc Fault, Installation Quality Issues.

Neermoor BESS Incident (April 2024): An incident, including an explosion that injured firefighters, occurred at a BESS facility. Similar to the Gansu, China case, suspected causes involve compatibility risks and integration issues in a multi-vendor (‘patchwork’) system.

Possible Root Causes: System Integration Risk (Compatibility Issues), Commissioning Error, Control Failure, potential Gas Accumulation & Explosion.

India

Nagpur Metro Station Rooftop Solar Cable Fire (Recent, Pre-May 2025): A minor fire reportedly occurred in the cable system of a rooftop solar panel installation at a metro station. It was suspected to be caused by a short circuit resulting from intense heat and a fault in wiring within a tin shed. Services were halted briefly.[28]

Possible Root Causes: Wiring Fault, Electrical Short Circuit, Overheating, potential Environmental Factor (Heat).

South Korea

Multiple BESS Fires (Various Locations, 2017-2022): South Korea experienced a significant number of BESS fires (reportedly over 30 incidents starting around 2017), leading to governmental investigations and a temporary moratorium. Incidents occurred at various sites, including Pyeongchang-gun (Sept 2019), Hongseong-gun (April 2021, PV+ESS), Jinjingmian Solar Park (Dec 2022), Southern Ulsan (Jan 2022), and a large 103 MW ESS at the Hyundai Steel Plant in Incheon (Sept 2022). While detailed public root cause analyses for each were often limited, investigations pointed toward a combination of factors in different incidents, including potential battery cell defects, inadequate system integration, insufficient operational monitoring, and protection logic (especially regarding SOC limits and fault detection), and installation environmental factors (e.g., humidity).[21]

Possible Root Causes: Varied across incidents - Internal Defects (Manufacturing), System Integration Risk, Control Failures (Monitoring/Protection Logic), Installation Issues, Environmental Factors.

ARICELL Battery Factory Fire (Hwaseong - June 2024): A devastating fire at a primary lithium battery manufacturing factory resulted in numerous fatalities. While not an operational BESS failure, this incident starkly highlights the significant fire and explosion hazards associated with battery materials and the manufacturing process itself. [29]

Possible Root Cause (General): Manufacturing Process Hazards.

United Kingdom (UK)

Thurrock BESS Fire (Essex - February 2025): A fire occurred within a single containerised battery unit at a large (300 MW/600 MWh) BESS site during construction (before operation). The fire was contained in the unit and extinguished within 24 hours, with effective site safety planning (compliance with NFPA standards, spacing, and water supply) credited for preventing the spread. The root cause is under investigation.[30]

Possible Root Causes: Under Investigation - Construction Phase Incident.

United States (USA)

Walmart Rooftop PV Fires (Multiple Stores, 2012-2018): Retail giant Walmart experienced fires linked to rooftop solar installations (provided by Tesla/SolarCity) at seven stores over several years, including three in quick succession in 2018 (Ohio, Maryland, California). Walmart sued Tesla, alleging negligent installation and maintenance practices, citing issues like improper grounding, visible defects in panels/wiring, and the use of personnel lacking basic solar training. This series of incidents highlighted risks associated with large-scale deployment programmes if quality control and proper procedures are not maintained.[31]

Possible Root Causes: Installation Quality Issues (Improper Grounding, Defective Workmanship), Inadequate Maintenance/Inspection, Lack of Expertise/Knowledge.

Amazon Rooftop PV Fires & Shutdown (Multiple Facilities, ~2020-2022): Amazon proactively shut down its North American rooftop solar installations after experiencing multiple "critical fire or arc flash events" (at least 6 incidents noted by mid-2022). One specific incident at a warehouse in Perryville, Maryland (June 2021) caused significant damage (USD 500k) and was officially attributed to an "unspecified event involving the solar panel system." Internal reports noted that the rate of dangerous incidents was above industry averages.[32]

Possible Root Causes: Varied - likely included DC Arc Faults, Electrical Faults (unspecified), and potential Installation Quality or Component Issues across multiple sites.

Moss Landing BESS Fires (Monterey County, California—2021, 2022, Jan 2025): The world's largest BESS facility experienced multiple incidents. A malfunction in September 2021 damaged ~7% of modules. Another event occurred in 2022. In January 2025, a major fire broke out, requiring the evacuation of ~1,500 residents due to smoke. The fire burned for days and even reignited weeks later. Failure of detection/suppression systems was noted as a factor in previous events.[33],[34] Investigations are ongoing, but the incidents have spurred significant regulatory review and safety concerns, alongside environmental/health worries due to potential contamination.[35]

Possible Root Causes: Under Investigation (Multiple Incidents) - likely complex involving potential Component Failure, Control Failures, Thermal Runaway, Reignition Issues. highlights systemic risks in very large-scale BESS.

3.3.3. Lessons Learned

Comparing the identified root causes of previous study cases (ASEAN and Global) reveals significant overlap and some differences in emphasis. Installation quality issues (including poor workmanship, lack of expertise, inadequate site assessment, non-adherence to standards) are a central recurring theme for PV systems both globally and within the ASEAN examples analysed. Specific component failures like faulty DC isolators (highlighted in Australia) or connectors leading to DC arcs (seen in the Philippines, Singapore, and globally) are also common PV ignition sources. The critical need for RSD functionality was highlighted in multiple ASEAN cases involving emergency response. For BESS, global incidents point strongly toward internal factors like manufacturing defects in cells, complex system integration challenges (especially multi-vendor systems), control system failures (BMS/sensors), and inadequate thermal management as frequent root causes, particularly in larger-scale deployments. While the ASEAN BESS examples were fewer in the reviewed set, vigilance across this broader spectrum of potential internal BESS failure modes identified globally will be crucial as its deployment scales up.

Numerous global incidents have been documented, particularly in regions with longer histories or larger deployment scales (like the USA, China, South Korea, Australia, Germany); however, the number of specific, publicly reported, major incidents identified within ASEAN appears lower based on this compilation. It is crucial to remember the disclaimer: this compilation relies on publicly available information and may not capture all events. Potential factors contributing to this observed difference could include varying levels of market maturity and the scale of deployments (fewer very large-scale systems historically compared to some global markets), differences in mandatory incident reporting regulations and public disclosure practices, varying media coverage, and potentially historical differences in the specificity or enforcement of safety standards. Therefore, the lower number of reported ASEAN cases should not be interpreted as inherently lower risk, but rather highlights a potential need for enhanced region-specific data collection and incident analysis to understand local safety challenges accurately.

Drawing insights from both regional and global experiences, the following categorised lessons are particularly relevant for improving rooftop PV and BESS safety practices within ASEAN countries:

<u>Key Lessons for Rooftop PV Safety in ASEAN</u>

Elevate Installation Quality and Mandate Expertise: The high frequency of incidents linked to poor installation quality (faulty connections, improper grounding, inadequate component sealing – seen in the Philippines, Singapore, Australia) and lack of expertise (Philippines, Malaysia electrocutions due to proximity hazards/poor planning) is a critical concern.

Action: Promote and enforce certification/training programmes for PV installers, focusing on electrical safety, proper connection techniques (crimping, torque), cable management, grounding/bonding best practices, and crucial site hazard assessment (especially working near existing power lines or at heights). Emphasise adherence to established codes like IEC 60364.

Prioritise Integration of Advanced Safety Technologies (RSD & AFCI): Multiple ASEAN incidents demonstrate the severe consequences (hindered firefighting, injury/fatality) of lacking RSD. Given the high DC voltages present on rooftops, implementing RSD should be a priority for new installations and should be considered for retrofits to protect occupants and emergency responders (Thailand Telecom/Singapore workers). Similarly, given DC arcing from connectors or faults as a common fire ignition source (Philippines/Singapore cases), mandating certified DC AFCIs designed for PV systems (per IEC 63027/UL 1699B) is a key preventative measure against fire.

Strengthen Grounding and Lightning/Surge Protection Practices: The recent lightning incident in Indonesia highlights the vulnerability of electrical systems in high-lightning regions of ASEAN. Robust equipment grounding and effective equipotential bonding are fundamental safety measures. Poor grounding and inadequate surge protection devices (SPDs) can significantly increase risk by allowing dangerous fault current paths and exposing equipment to surge damage. Beyond these basic requirements, there is a clear need for more detailed guidance and standards that address the specific challenges of rooftop grounding. Additionally, correctly rated SPDs must be installed on both the DC and AC sides of the system, in compliance with relevant lightning protection standards such as IEC 62305. Equally important, maintaining the long-term effectiveness of SPDs requires the implementation of routine inspection and testing protocols.

Establish Robust Maintenance and Inspection Protocols: Component degradation and failure over time contribute to risk (e.g., Australian DC isolator issues linked partly to ageing/ lack of maintenance). Clear guidelines for periodic inspection and preventative maintenance of rooftop PV systems should be encouraged or mandated in ASEAN. Inspections should include visual checks (cable damage, mounting security), connection tightness tests (thermal imaging can help), insulation resistance testing, and functional checks of safety devices like isolators and AFCIs/RSD if installed. Elaborate on what needs inspection (connections, isolators, insulation) and why (degradation, environmental impact – lessons from Australian isolator issues).

Key Lessons for BESS Safety in ASEAN

Mandate Certified Components and Quality Assurance: All BESS components deployed in ASEAN – particularly battery cells/modules, BMS, and PCS – must be appropriate for the application and certified to relevant international safety standards (e.g., IEC 62619, IEC 63056, UL 1973 for batteries; IEC 62933 for battery energy storage systems). Explain the consequences of using flawed components (global manufacturing defect cases). Stress verification/certification and rigorous quality control in manufacturing and procurement.

Adopt Comprehensive System Safety Design Standards: As BESS projects scale up in ASEAN, designs must incorporate multiple layers of safety based on international best practices and standards like the IEC 62933 series and NFPA 855. Elaborate on the specific safety systems needed (BMS, TMS, Fire Safety - detection, suppression, venting) and why they are critical, referencing global cases like Victoria (cooling failure). Mention the relevance of UL 9540A testing for validating thermal management and propagation prevention.

Ensure Rigorous System Integration & Commissioning: Global incidents highlight risks from poor integration, especially in multi-vendor systems (China, Germany examples). Add detail on what can go wrong (compatibility clashes, incorrect settings), referencing the "patchwork" system risks. Thorough system integration studies, testing, and validated commissioning procedures by qualified personnel are crucial before operation (avoiding errors as seen in the Hainan case).Interoperability issues between the components of BESS system are crucial to ensure the functional safety of BESS systems. The communication of different manufacturers' or suppliers' equipment need to have complete integration tests prior to operation.

Address Lifecycle Risks (Transport, Installation Environment): Safety protocols must cover potential damage during transportation (vibration/shock - China transport fire) and ensure installations are protected from environmental risks like water ingress (learning from Elkhorn/Bouldercum cases) through appropriate enclosure IP ratings, sealing, and site design from the outset.

Implement Continuous Monitoring & Emergency Preparedness: Beyond the BMS, system-level monitoring should track performance and health for early anomaly detection. Develop clear Standard Operating Procedures (SOPs) and Emergency Response Plans (ERPs), coordinated with local first responders trained on specific BESS hazards, including thermal runaway, toxic gases, and stranded energy, with appropriate response tactics.

Chapter 4

Assessment of ASEAN Electrical Safety Frameworks for Rooftop PV and BESS

As ASEAN advances its energy transition through the adoption of rooftop PV and BESS, ensuring the electrical safety of these installations is fundamentally important for preventing hazards like shocks and fires, thereby building essential public and investor trust. The significance of robust electrical safety frameworks is rapidly growing across the region due to factors including the accelerated deployment pace driven by rising energy demands, the heightened risks associated with installations in densely populated urban centres, the technical challenges of safely integrating numerous distributed systems into national grids, the need to maintain economic confidence for sustained investment, and the necessity for systems to be resilient against prevalent climate-related threats like extreme weather.

Recognising these critical aspects, this chapter provides assessment of the current electrical safety landscape for PV and BESS within ASEAN by reviewing applicable international standards, examining existing national regulations and codes across member states, mapping key stakeholders, evaluating the completeness of current frameworks, identifying crucial gaps, and discussing the implications for necessary regional harmonisation.

4.1. International Electrical Safety Standards Framework

A robust international framework underpins the electrical safety of PV and BESS installations, primarily developed by bodies like the IEC and IEEE. These standards provide necessary guidelines, testing procedures, and safety requirements designed to prevent harm from electrical hazards such as shocks, fires, arc flashes, and explosions. Adherence to these standards is crucial for reliable RE systems, especially given that real-world incidents highlight potential failure points like water ingress or internal cell defects leading to thermal runaway.

A comprehensive approach to PV and BESS electrical safety involves referencing standards at two distinct levels. The first level, as compiled in a general list (similar to Table 2-2), establishes the high-level framework by curating fundamental electrical safety standards highly relevant to PV and BESS installations. The second level, found in a more detailed list (Table 4-1), provides specific technical standards that apply directly to system architecture, components, and applications such as rooftop installations.

The connection between these two levels is demonstrated by a core set of standards that appear on both lists, signifying their foundational importance across both general principles and specific technical design.

For example, the IEC 60364 series serve as a broad, high-level standard for all low-voltage electrical installations, while its specific parts are also technically essential for PV system design. For grid integration, IEEE 1547 provides the general safety framework for interconnection, which is then detailed as a specific technical requirement for system performance.

This principle extends to system architecture, where general component safety standards are elaborated upon in the technical list. This includes the IEC 62548 series for PV array design, the IEC 62109 series for inverter safety, and the comprehensive IEC 62933 series for Battery Energy Storage Systems. Finally, a general safety hazard like an arc fault is addressed by specific technical standards such as IEC 63027 and UL 1699B, which detail the precise requirements for arc fault circuit interruption technology.

Table 4-1 Key International Standards for Solar PV and BESS

Category	Standard(s)	Key Focus Areas
PV - General Safety	IEC 60364-7-712, IEC 62548-1 & IEC 62548-2, IEC 62446-1, IEC 61730, IEC 62109-1&IEC62109-2, IEC 60364-5-54	LV installation requirements, array design, testing/documentation/ maintenance, module safety, inverter safety, earthing
PV - Grounding/ Earth Fault	IEEE 2778, IEC 63112	Grounding (utility-scale/ground-mount), Earth Fault Protection (ground-mount) - Note rooftop gap
PV - Arc Fault Protection	IEC 63027,UL1699B, GB/T 39750-2021	DC arc fault detection and interruption requirements and testing
PV - Rapid Shutdown (RSD)	NEC 690.12, VDE-AR-E 2100-712, T/ CECS 941-2021	Rapid de-energization of array conductors for firefighter safety, voltage/time limits
PV - Components	IEC 62852, IEC 60269-6	DC connector safety, Fuse standards for PV circuits
BESS - System Safety	IEC 62933 -5-1 & IEC 62933-5-2UL 9540	Overall system safety, risk assessment, grid integration safety, hazard mitigation (electrical, thermal, chemical, etc.)
BESS - Installation	IEC 62933-3, NFPA 855, AS/NZS 5139, IEC 62485-2, VDE-AR-E 2510-50, TR 77	System planning, installation practices, siting, commissioning, hazard mitigation, ventilation
BESS - Battery Safety	IEC 62619, IEC 63056, UL 1973	Safety requirements and testing for lithium-ion cells/batteries in industrial/stationary ESS applications
BESS - Functional Safety	IEC 60730-1 Annex H, IEC 61508, ISO 13849, UL 991+UL 1998	Safety requirements for control systems (e.g., BMS)
BESS - EMC	IEC/EN 61000-6 Series	Electromagnetic compatibility requirements
BESS - Thermal Runaway	UL 9540A	Test method for evaluating fire propagation from thermal runaway
BESS-Transport	UN38.3	Test to ensure the safety of lithium batteries during transportation
BESS – PCS Safety	IEC 62477-1, UL 1741	Safety requirements for Power Conversion Systems used with BESS
Grid Interconnection	IEEE 1547	Interconnection requirements, interoperability, performance (ride-through, voltage/frequency response)
General Electrical	IEC 60364 (esp. -4-41), IEC 61439	General LV installation safety, protection against electric shock, LV switchgear assemblies

4.1.1. Solar PV

Core IEC Standards: Often considered the foundation, addressing ~80% of safety issues:[9]

- **IEC 60364-7-712 (Low voltage electrical installations - Part 7-712: PV power supply installations)**: This crucial standard applies to the electrical installation from modules to the connection point, including interfaces with energy storage. It mandates specific safety measures addressing the unique characteristics of PV DC systems:
    - **Electric Shock Protection (712.41)**: Requires designs that consider the maximum open-circuit voltage and ensuring protection through measures like double/reinforced

insulation or SELV/PELV, recognising the DC side remains energised even when the AC side is off.

- **Thermal Effects/Fire Protection (712.42)**: Clause 712.421.101 specifically addresses DC arc fault effects, recommending additional measures like AFPE compliant with **IEC 63027**, especially for high-risk locations or Building-Integrated PV (BIPV).
- **Insulation Fault Protection (712.421.102)**: Mandates protection (unless the system is <60 V and <70 W) via RCD or IMD to detect faults, trigger alarms, and/or initiate disconnection, preventing potential fire or shock hazards. Inverter compliance with **IEC 62109** often covers these functions.
- **Overcurrent Protection (712.430)**: Addresses protection needs considering potential overcurrent from parallel strings or backfeed from certain types of Power Conversion Equipment (PCE).
- **Overvoltage Protection (712.443)**: Requires protection against transient overvoltages (lightning or switching) based on **IEC 60364-4-44,** or a risk assessment comparing cable length to a critical length derived from the local lightning ground flash density.
- **Component Compliance (712.511)**: Mandates that PV modules comply with **IEC 61730**, PCE with **IEC 62109**, and switchgear/combiner boxes with relevant parts of **IEC 61439**.

- **IEC 62548 (PV arrays - Design requirements)**: Sets out requirements for array design, including DC wiring, protection devices, switching, and earthing provisions, but excludes energy storage and AC/DC distribution networks supplying loads. It should be used in coordination with **IEC 60364-7-712**. As noted previously, potential gaps may exist regarding detailed cable derating and comprehensive DC fault clearing.
- **IEC 62446-1 (PV systems - Requirements for testing, documentation, and maintenance - Part 1)**: Defines the documentation required for handover, commissioning tests, and inspection criteria to verify safe installation and correct operation of grid-connected systems (excluding energy storage). It also serves as a basis for periodic retesting.

Grounding and Earth Fault Protection: Improper or failed grounding is a critical issue identified in PV rooftop fire incidents, often linked to short circuits. A specific gap for rooftop applications persists:

- Standards like **IEEE 2778-2020** (utility-scale ground-mount) and **IEC 63112:2021** (earth fault protection, primarily ground-mount) do not fully address the unique grounding needs of rooftop PV concerning lightning and short circuits.
- This identified gap can lead to installations relying solely on potentially inadequate inverter SPDs, especially if SPD health isn't monitored. General earthing requirements are in **IEC 60364-5-54**.

Arc Fault Protection: Essential due to the high fire risk from DC arcs.[11]

- **IEC 63027** defines requirements and test methods (using specific PV source models and test setups) for AFPE, mandated by **IEC 60364-7-712** in high-risk situations. It aligns closely with **UL 1699B**.

Rapid Shutdown (RSD): Enhances safety for firefighters, first respondents, installers, and O&M staff.

- Standards like **NEC 2020 Section 690.12, VDE-AR-E 2100-712, T/CECS 941-2021**, and others mandate rapid voltage reduction within set boundaries and timeframes.

Component Safety and Others: Includes **IEC 61730** (module safety), **IEC 62109** (inverter safety), **IEC 62852** (connector safety), and **IEC 60269-6** (PV fuse standards).

4.1.2. BESS

The international standards framework for BESS addresses safety and performance across multiple levels, from the battery cell to the complete installed system. This is crucial as incidents often stem from installation, maintenance, internal defects (e.g., cell mismatch leading to thermal runaway), control failures, or external factors like water ingress.

The BESS standardisation landscape is relatively young, but has evolved significantly since ~2016-2017, when key system-level and installation standards were published.[12],[36]

Layered Standards Approach: BESS safety relies on standards covering different system components and aspects:

- **Cell Level**: Focuses on the fundamental battery unit. Key standards include **IEC/EN 62619** (industrial Li-ion safety), **ANSI/CAN/UL 1973** (US/Canada safety), and **IEC/EN 62620** (performance). Chemical regulations like the EU Battery Directive are also relevant.
- **Pack/Module Level**: Addresses safety of assembled battery units. Relevant standards include **IEC 62933 series, IEC/EN 62619, ANSI/CAN/UL 1973**, and regional guides like **VDE-AR-N 2510-50** (Germany). Functional safety for control systems (like BMS) is critical, covered by standards such as **IEC 60730-1 Annex H**, **IEC 61508**, and **UL 991+UL 1998**. Electromagnetic Compatibility (EMC) is addressed by the **IEC/EN 61000-6 series**.
- **PCS Level**: Covers the inverters/converters used with BESS. Key safety standards include **EN 62477-1** and **UL 1741**. Grid connection compliance often references **IEEE 1547/1547.1**, **EN 50549 series**, or **AS/NZS 4777.2**.
- **System Level**: Addresses the entire integrated BESS. The **IEC 62933** series is paramount here, alongside **UL 9540** (US/Canada system safety). Fire safety testing methods are detailed in **UL 9540A** together with Hazard Mitigation Analysis (HMA) to ensure that risks identified are properly addressed.

IEC 62933 Series (Electrical Energy Storage Systems): This key IEC series focuses specifically on system aspects of ESS. Its primary sections include Part 1 – Terminology, Part 2 - Unit Parameters and Testing Methods, Part 3 - Planning and Installation - Provides crucial guidelines for system planning, design, installation, O&M, and integration, Part 4 -Environmental Issues, and Part 5 - Safety Considerations - This part is vital and includes several sub-parts:

- **IEC 62933-5-1 (General Safety)**: Covers hazard identification, risk assessment methodology (evaluating likelihood and severity, determining tolerable risk), mitigation requirements, validation/ testing, and documentation for grid-integrated systems. Requires calculated overcurrent protection design based on fault levels, conductor capacity, etc., referencing **IEC 60364-4-43**.
- **IEC 62933-5-2 (Electrochemical Systems Safety)**: Specifies detailed safety requirements for electrochemical BESS (e.g., Li-ion). Key areas include hazard ID (electrical, mechanical, chemical, environmental); protections against electrical hazards (overvoltage, short circuit); critical thermal management to prevent thermal runaway; chemical hazard control (leakage, gas); fire safety (detection, suppression); system control/monitoring (voltage, temp, SoC); mechanical hazard protection; safe installation/ maintenance procedures (personnel safety, LOTO); and environmental robustness.
- **IEC 62933-5-3 (Unplanned Modification)**: Addresses safety when performing unplanned modifications.
- **IEC 62933-5-4 (Li-ion Test Methods - Draft)**: Will provide specific safety test methods for Li-ion systems.

Battery-Specific Safety: Standards like **IEC 62619 (industrial Li-ion)** and **IEC 63056 (Li-ion specifically for ESS)** define intrinsic safety requirements. **UL 1973** is the North American equivalent.

Installation Standards: Beyond product/system certification, dedicated installation standards are crucial for safe siting, design, construction, commissioning, and maintenance. Prominent examples include **NFPA 855** (USA), **AS/NZS 5139** (AU/NZ), **VDE-AR-E 2510-50** (Germany), and **TR 77** (Singapore). **IEC 62485-2** also addresses installation safety for secondary batteries.

Protection Systems & Mitigation: Effective safety relies on integrated systems like BMS for monitoring and control, Thermal Management Systems (TMS), and properly designed protection against overcurrent, faults, and environmental factors. Advanced safety designs often incorporate multi-level protection strategies (cell, pack, rack, system), including measures for thermal runaway prevention/mitigation, explosion protection (venting, suppression), and fire extinguishing.

4.2. Review of Existing Regulations and Standards in ASEAN Countries

The adoption, implementation, and enforcement of electrical safety regulations and standards for PV and BESS vary significantly across the AMS. Some countries have established comprehensive national frameworks aligned with international standards, while others rely on general electrical codes, project-specific requirements, or are still in the process of developing dedicated regulations. Table 4-2 provides a summary overview elaborated upon in the subsequent country-specific sections.

Table 4-2 Status of PV and BESS Electrical Safety Regulations in ASEAN

Country	PV Regulation Status	BESS Regulation Status	Key Standards Referenced	Primary Regulatory Body	Enforcement Emphasis
Brunei Darussalam	Refers to IEC/IEEE via technical docs	Refers to IEC/IEEE via technical docs	IEC 60364, 61730, 62109, IEEE 1547	DOE, DES, SHENA	Financier-driven; lacks codified NEC
Cambodia	Formal EAC regulation (Rooftop) exists	No dedicated regulation; Gap	IEC 60364, 61730, UL 1703 (PV); IEC 62933 (BESS practice)	EAC, MME, EDC	Partial (PV); Financier-driven (BESS)
Indonesia	Permen ESDM, PLN SPLN	No specific regulation; Gap	IEC 60364-7-712, 61730, 62109 (PV practice); IEC 62933, 62619 (BESS practice)	ESDM, PLN	Fragmented; Financier/ Developer-driven
Lao PDR	General (LEPTS)	Not specific; Gap	IEC 60364, 61730, 62109, 62933, IEEE 1547 (practice/ projects)	MEM, EDL	Financier/Donor-driven; Development stage

Malaysia	MS/ESAH adopts IEC	ESAH references IEC/UL/NFPA	MS IEC 60364, 61730, 62109; IEC 62933, UL 9540, NFPA 855	ST, TNB, SEDA	Formal, Codified, Enforced
Myanmar	No specific regulation	No specific regulation; Gap	IEC 60364, 61730, 62109, 62933 (practice via partners)	MOEP	Financier/Donor-driven; Development stage
Philippines	Formal Code exists (PEC 2017 covers PV)	No dedicated regulation in PEC; Gap	PEC 2017 (NEC based); IEC 62933, NEC 706 (BESS practice)	DOE, ERC, IIEE (PEC dev.), Local Govt.	Formal (PV); Financier-driven (BESS)
Singapore	SS 638 mandatory	TR 77 widely adopted	SS 638 (based on IEC 60364), IEC 61730, TR 77 (BESS)	EMA, SSC, Enterprise SG, BCA, SCDF; Requires LEW installation	Formal, Codified, Multi-agency Enforced
Thailand	EIT/Utility Codes	Grid Code integrates BESS	EE 2001-56/Rooftop Code (IEC 60364 based), IEC 61730, 62933	EGAT, MEA, PEA, TISI, ERC	Formal, Structured, Implemented
Viet Nam	Grid Code; Lacks safety details	No dedicated regulation; Gap	IEC 60364, 61730, 62933 (practice via pilots/financiers)	MOIT, ERAV, EVN	Evolving; Financier/Pilot-driven

4.2.1.  Brunei Darussalam

Regulatory Bodies: Key institutions include the Department of Electrical Services (DES) under the Department of Energy (handling policy/infrastructure) and the *Autoriti Elektrik Negara Brunei Darussalam* (AENBD), which serves as the primary regulatory authority enforcing the Electricity Act. In 2023, the Electrical Safety Committee (ESCOM), co-chaired by AENBD and the Safety, Health, and Environment National Authority (SHENA), was established to promote compliance and improve electrical safety standards.

PV & BESS Regulation Status: While Brunei needs a formally codified National Electrical Code (NEC) that could complement the existing official documents, such as National Grid Code and Electrical Installation Requirements issued by AENBD and the Department of Energy regulating the safety and installation of Solar PV, especially within T&D networks.

Key Standards Referenced: While these documents don't explicitly reference international standards, they incorporate globally accepted principles and reflect alignment with key standards like IEC 60364 (LV installations), IEC 61730 (PV module safety), IEC 62109 (converter safety), and IEEE 1547 (interconnection).

Adoption & Enforcement: The existing documents provide a foundational basis, but without a specific national code the adoption and enforcement of detailed PV/BESS safety standards often rely heavily on project-specific requirements. To ensure alignment with global norms (IEC, IEEE, UL), tenders issued in Brunei incorporate international standards and best practices – often guided by the expectation of developers or international financiers to uphold safety, quality, and performance.

4.2.2. Cambodia

Regulatory Bodies: The Electricity Authority of Cambodia (EAC) supervises the sector, while *Electricité du Cambodge* (EDC) issues the Grid Code. Both agencies are working in coordination with the Ministry of Mines and Energy (MME)

PV Regulation Status: As of late 2024, specific regulations from EAC address rooftop PV electrical safety installations, outlining technical requirements aligned with standards such as IEC 60364, IEC 61730, and ANSI/UL 1703.

BESS Regulation Status: Cambodia currently lacks dedicated national regulations for BESS installation safety. Publicly available information on applicable standards is limited.

Adoption & Enforcement: Regulations exist for PV. For BESS, prevailing practices rely on international best practices (like IEC 62933, 62446) and standards mandated by international financiers (World Bank, ADB, IFC), especially for utility-scale or donor-funded projects. Final technical specifications, including safety, are often determined by financier requirements to meet bankability and risk criteria in the absence of formal domestic BESS regulation. Further development of national BESS codes is anticipated.

4.2.3. Indonesia

Regulatory Bodies: The Ministry of Energy and Mineral Resources (ESDM) and the state utility PLN are key entities.

PV Regulation Status: No single comprehensive regulation exists. Permen ESDM No. 2 of 2024 (rooftop PV) and PLN standard SPLN D3.015-1:2020 provide partial technical requirements (certified inverters, overcurrent protection, grounding, disconnects).

BESS Regulation Status: Provisions remain limited and do not explicitly cover aspects of BESS electrical installation safety.

Adoption & Enforcement: Due to the lack of specific national regulations, project implementation heavily relies on the *de facto* adoption of international IEC standards (IEC 61730, 62109, 60364-7-712 for PV; IEC 62933, 62619 for BESS). This adoption is driven by both developers seeking reliable designs and financiers requiring compliance for due diligence. A unified, enforceable national regulation remains a critical gap.

4.2.4. Lao PDR

Regulatory Bodies: Regulation involves the Ministry of Energy and Mines (MEM) and *Electricité du Laos* (EDL).

PV & BESS Regulation Status: No specific National Grid Code or regulation explicitly governs PV/BESS electrical installation safety. The Lao Electric Power Technical Standards (LEPTS) provide general technical guidelines for electrical installations (grounding, protection, cables), but lack specifics for PV or BESS.

Key Standards Referenced: The regulatory environment draws heavily on international standards (IEC 60364, 61730, 62109; IEEE 1547) often applied on a project basis or influenced by regional initiatives (Greater Mekong Subregion - GMS).

Adoption & Enforcement: The framework is developmental. Project execution relies on a combination of developer best practices and financier requirements mandating adherence to international standards (IEC, IEEE) during due diligence and funding approval, ensuring technical quality despite the absence of dedicated national rules.

4.2.5. Malaysia

Regulatory Bodies: Authoritative bodies include the Energy Commission (*Suruhanjaya Tenaga*, ST), *Tenaga Nasional Berhad* (TNB), and the Sustainable Energy Development Authority (SEDA) Malaysia.

PV & BESS Regulation Status: Malaysia has established official regulations, technical documentation, national grid codes, handbooks, and guidelines providing specific and comprehensive governance for PV and BESS electrical installation safety connected to the distribution network.

Key Standards Referenced: A wide range of international standards have been adopted and implemented nationally. For PV, this includes IEC 60364-7-712, IEC 61730, and IEC 62109. For BESS, references include IEC 62933-5-1, UL 9540, and NFPA 855.

Adoption & Enforcement: These international standards are incorporated into the formal and structured national regulatory framework via Malaysian Standards (MS, adopting IEC) and key documents like TNB's Electricity Supply Application Handbook (ESAH), ensuring mandatory compliance and clear protocols for connection and safety.

4.2.6. Myanmar

Regulatory Bodies: The Ministry of Electric Power (MOEP) is the highest authority.

PV & BESS Regulation Status: As of the source document date, Myanmar lacks a grid code or national regulation specifically and comprehensively addressing PV/BESS electrical installation safety requirements. The existing Myanmar Electricity Grid Code is general and lacks these specifics. Technical provisions are considered under development.

Key Standards Referenced: In practice, safety assurance relies on referring international standards (IEC 60364, 61730 for PV; IEC 62933, 62109 for BESS/inverters).

Adoption & Enforcement: Implementation often follows technical guidelines derived from international collaborations (e.g., USAID, ADB) and project-specific requirements from developers or financiers mandating adherence to global standards (IEC, IEEE, UL) due to the absence of codified national regulations.

4.2.7. The Philippines

Regulatory Bodies: Electrical safety is primarily governed by the Philippine Electrical Code (PEC), developed by the IIEE and adopted/enforced by local authorities (Office of the Building Official) and electrical practitioners. The Department of Energy (DOE) and Energy Regulatory Commission (ERC) also play roles.

PV Regulation Status: PEC 2017 (largely based on US NEC and incorporating IEC 60364 principles) serves as the primary technical reference and includes coverage for PV system installation safety (protection, grounding, disconnects, including RSD).

BESS Regulation Status: There is no dedicated section for BESS within the PEC or other national codes. Safety considerations are inferred or adapted from international best practices (e.g., NEC Article 706, IEC 62933) without formal codification. DOE Circular No. DC2023-04-0008 provides a general framework, but lacks detailed installation safety guidelines.

Adoption & Enforcement: PV safety has a formal basis in the enforced PEC. For BESS, the significant regulatory gap means implementation follows standards set by developers or mandated by international financiers (IEC, UL, NFPA) as part of funding/risk mitigation.

4.2.8. Singapore

Regulatory Bodies: A multi-agency structure involves the Energy Market Authority (EMA, primary regulator), Singapore Standards Council (SSC), Enterprise Singapore, Building and Construction Authority (BCA), and Singapore Civil Defence Force (SCDF).

PV & BESS Regulation Status: Singapore has a comprehensive, well-structured framework. Electrical safety is governed by the mandatory Singapore Standard SS 638 (Code of Practice for Electrical Installations, adopting IEC 60364 principles). EMA enforces this and the Grid Code/Technical Requirements for PV connections. For BESS, Technical Reference TR 77:2020 provides detailed technical guidance (siting, ventilation, thermal runaway, fire protection integration) and is widely adopted as best practice. BCA and SCDF regulate structural and fire safety aspects.

Key Standards Referenced: SS 638 (based on IEC 60364), IEC 61730 (referenced for PV components), TR 77 (for BESS).

Adoption & Enforcement: High level of adoption and enforcement is ensured through mandatory compliance with SS 638, EMA oversight, and the requirement for all installations to be done by certified Licensed Electrical Workers (LEWs).

4.2.9. Thailand

Regulatory Bodies: Key institutions include the Electricity Generating Authority of Thailand (EGAT), Thai Industrial Standards Institute (TISI), Metropolitan Electricity Authority (MEA), Provincial Electricity Authority (PEA), and the Energy Regulatory Commission (ERC).

PV & BESS Regulation Status: Thailand has established a comprehensive framework specifically addressing PV and BESS electrical safety installation, encompassing grid connectivity and safe installation practices (hazard protection, wiring, grounding, testing, certification).

Key Standards Referenced: The framework uses national standards developed by Engineering Institute of Thailand (EIT), such as the Electrical Installation Standard for Thailand (e.g., EE 2001-56, EIT- 022013-22 or newer rooftop codes like B.E. 2565, referenced in Ref 3), which incorporate international benchmarks (IEC 60364, 61730, 62933). The EGAT Grid Code includes detailed technical requirements for PV/BESS integration (e.g., dynamic modelling). TISI sets relevant product standards.

Adoption & Enforcement: Implementation is supported by collaboration amongst agencies providing guidelines, inspection protocols, and certification, reflecting a well-structured and internationally aligned approach with national implementation mechanisms.

4.2.10. Viet Nam

Regulatory Bodies: Oversight involves the Ministry of Industry and Trade (MOIT), Electricity Regulatory Authority of Viet Nam (ERAV), and Viet Nam Electricity (EVN).

PV & BESS Regulation Status: The framework is evolving and currently general rather than specific regarding electrical installation safety. The national Viet Nam Grid Code focuses on operational/connectivity standards. Rooftop PV regulations (Decision 13/2020, Circular 18/2020) provide technical guidance, but lack comprehensive installation safety details (grounding, protection, RSD, fire safety). Viet Nam has yet to adopt dedicated regulations governing BESS electrical installation safety.

Key Standards Referenced: Currently, no national electrical code provides a legally binding, detailed safety framework for PV/BESS. Practice relies on international standards (IEC 60364, 61730, 62933) adopted through engineering best practices or requirements in pilot projects supported by international partners (ADB, GIZ).

Adoption & Enforcement: Without comprehensive national regulations, project execution and safety standards are typically guided by requirements set by developers or international financiers imposing global standards (IEC, UL, NFPA) for funding and implementation.

4.3. Standards Gaps for Rooftop PV and BESS in ASEAN

While many ASEAN countries reference international standards, specific gaps persist in the detailed content and application of these standards within national frameworks, particularly when compared to rapidly evolving technology and international best practices. These gaps present tangible safety risks.

Rooftop PV Grounding and Lightning Protection: A critical gap previously identified is the lack of a dedicated, comprehensive international standard specifically tailored for rooftop PV system grounding and lightning protection. General LV earthing standards (IEC 60364-5-54) or those for utility-scale, ground-mount systems (IEEE 2778) do not adequately address the unique exposure and environment of rooftop installations, particularly concerning direct or indirect lightning strikes (a high risk in tropical ASEAN) and effective fault current dissipation to prevent fires.

Past incidents involving rooftop PV fires linked to short circuits where grounding systems failed to perform adequately underscore this danger. International best practices, such as those embedded within the US NEC (Art. 690) and lightning protection standards (IEC 62305 series), emphasise robust and correctly designed grounding and bonding as fundamental safety requirements. The absence of a clear, specific standard for rooftop applications makes this area compulsory to address.

This lack of a definitive international rooftop standard translates into inconsistent practices across ASEAN, particularly in countries where detailed national codes are still developing or rely on general interpretations, including Brunei, Lao PDR, Myanmar, and potentially others where specific enforcement mechanisms are weak. Installers might default to relying solely on inverter SPDs or minimum general requirements, which may prove insufficient.

BESS Thermal & Chemical Safety Specificity: While foundational standards like IEC 62619/63056 address battery safety and IEC 62933-5-2 outlines system safety requirements, including thermal management and chemical hazards, a significant gap exists in many ASEAN nations regarding the codification and enforcement of detailed, mandatory installation standards that translate these principles into specific site requirements. Learning from numerous global BESS fire and explosion incidents, often involving lithium-ion thermal runaway or flammable off-gas ignition, international best practices now incorporate highly specific requirements. Standards like NFPA 855 (USA) and VDE-AR-E 2510-50 (Germany) mandate aspects like minimum separation distances, container/room ventilation rates, specific fire detection and suppression systems (often multi-stage), explosion venting/prevention based on UL 9540A test results, and stringent BMS functionalities. Addressing thermal and chemical safety with such specificity is compulsory for safe deployment.

The major regulatory gap for BESS in countries like the Philippines, Indonesia, Cambodia, Viet Nam, Myanmar, Lao PDR, and Brunei directly implies the absence of these compulsory, detailed installation safety codes. Even where IEC 62933 is referenced (e.g., Brunei, Thailand, Malaysia, Singapore via TR 77), the level of detail and mandatory enforcement specific to thermal/chemical hazard mitigation in the installation context might still vary compared to the prescriptive nature of NFPA 855 or VDE-AR-E 2510-50.

HV/LV Differentiation and Scalability: Standards often lack clear differentiation in requirements based on system scale (e.g., residential rooftop vs. large commercial/industrial rooftop vs. utility-scale). Applying low-voltage residential rules to larger, more complex systems might be inadequate, while imposing utility-scale requirements on small systems can be overly burdensome. Best practices involve requirements tailored to voltage level, capacity, and application complexity.

This lack of clear scaling in requirements could pose challenges across various ASEAN countries, as they see deployment across different scales. If regulators apply generic rules, this could potentially lead to under-protected larger systems or over-engineered smaller ones.

Standards for New Components & Technologies: The rapid pace of innovation in PV and BESS technology often outstrips the standards development cycle. Key areas where standards might be lagging or inconsistently applied include:

- **Grid-Forming Inverters**: While promising for grid stability, these inverters have different control logic and fault current characteristics than traditional grid-following types. Ensuring their safe interaction with existing grid protection and defining specific performance/safety validation requirements is an emerging need not yet fully covered by standard grid codes.
- **Cybersecurity**: The increasing digitalisation and network connectivity of PV inverters, BESS BMS, and energy management systems introduce vulnerabilities to cyberattacks. Compromised systems could lead to unsafe operation (e.g., forced overcharging) or grid instability. While general cybersecurity frameworks exist (e.g., IEC 62443), specific mandatory cybersecurity standards and testing protocols for DER equipment are still evolving globally and likely underdeveloped in most ASEAN regulatory frameworks.
- **Advanced Battery Chemistries**: As new battery chemistries emerge, existing safety standards predominantly focused on specific lithium-ion types (LFP, NMC) may need updates or supplements to address potentially different failure modes or safety requirements.

4.4. Governance Structures, Stakeholder Coordination, and Regulatory Gaps

The effectiveness of electrical safety frameworks for PV and BESS in ASEAN is intrinsically linked to the specific governance structures within each member state, the roles assigned to various national stakeholders, and the level of coordination achieved amongst them. Analysing these aspects reveals both established systems and significant variations or gaps across the region that influence regulatory formulation, adoption, and enforcement. Table 4-3 identifies the primary governmental and related bodies involved in overseeing aspects of electrical safety, standards and regulation for the power sector, including PV and BESS, in each ASEAN country.[37]

Table 4-3 Key Entities Involved in PV/ BESS Electrical Safety Governance

Country	Policy/Primary Regulator	Standard Setting/ Adoption Body	Utility/Grid Operator	Enforcement/Inspection Body
Brunei Darussalam	DES (Dept. of Energy)/AENBD	AENBD (via tech docs)	DES	AENBD/SHENA
Cambodia	MME/EAC	EAC (references IEC/UL for PV)	EDC	EAC
Indonesia	MEMR (ESDM)	BSN (National Body)/ ESDM/PLN (SPLN)	PLN	ESDM/Local Inspectorates (Often Project/ Financier Driven)
Lao PDR	MEM	MEM/LEPTS	EDL	MEM/EDL
Malaysia	ST/SEDA	ST/Standards Malaysia (MS adopts IEC)	TNB	ST/TNB (via ESAH)
Myanmar	MOEP	MOEP (Standards underdeveloped)	MEPE/YESC	MOEP
Philippines	DOE/ERC	IIEE (develops PEC)/BPS (guides)	NGCP/DUs	Local Govt. (OBO enforces PEC)/ERC/DOE
Singapore	EMA	SSC/Enterprise SG (SS, TR)	SP Group	EMA (via LEWs)/BCA/SCDF
Thailand	ERC/Ministry of Energy	TISI/EIT	EGAT/MEA/ PEA	ERC/Utilities (MEA/PEA/EGAT)
Viet Nam	MOIT/ERAV	MOIT/Institute of Energy	EVN	MOIT / ERAV/EVN

Note: This table reflects primary entities mentioned in sources; roles can be complex and overlapping. Enforcement mechanisms vary significantly.

The stakeholders mapped above interact within national governance systems that shape the electrical safety landscape for PV and BESS. Key aspects influencing effectiveness include:

Clarity of Mandates and Lead Agencies: Countries like Singapore (EMA) and Malaysia (ST) benefit from having strong, clearly mandated lead regulatory agencies overseeing electrical safety, standards adoption and enforcement. In contrast, responsibilities in other nations might be distributed across multiple bodies (e.g., energy ministry, utility, separate safety authority like SHENA in Brunei involved via ESCOM), potentially leading to less focused oversight or coordination challenges, unless specific mechanisms like ESCOM are effective.

Stakeholder Coordination: Effective safety management requires seamless coordination, particularly between bodies setting policy/standards, utilities managing the grid, and entities enforcing rules on the ground. Singapore's multi-agency approach involving EMA, SSC, BCA, and SCDF exemplifies strong coordination for both electrical and related structural/fire safety. Where coordination is weaker or responsibilities are fragmented, developing and implementing cohesive safety strategies becomes more difficult, potentially contributing to the gaps observed.

National Standards Development & Adoption: The process for developing or adopting standards varies. Malaysia (via MS standards) and Singapore (via SS/TR) demonstrate robust national processes that formally integrate international IEC standards. Thailand also uses national standards developed via bodies like TISI and EIT alongside utility codes. In contrast, countries lacking dedicated NEC or specific PV/BESS codes (Brunei, Cambodia, Indonesia, Lao PDR, Myanmar, Viet Nam, and the Philippines for BESS) often rely on direct reference to IEC standards within technical guidelines or, more commonly, leave detailed standard adherence up to project proponents and financiers. This leads to a *de facto* adoption pattern, but lacks the uniformity and legal weight of formally adopted national standards.

Enforcement Mechanisms & Capacity: The governance structure dictates enforcement power. Mandatory requirements like Singapore's LEW system, or utility enforcement via grid connection codes (Malaysia, Thailand), provide strong compliance levers. In comparison, enforcement reliant solely on ministry oversight or local building official inspections (like in the Philippines for PEC) might face resource constraints or varying levels of technical expertise specific to PV/BESS. Where national enforcement is perceived as weak or inconsistent, the role of financiers in mandating international standards becomes crucial, but doesn't guarantee uniform safety levels across all installations (especially smaller ones not subject to financier scrutiny). A critical factor often highlighted is the need for adequate training and certification for installers and inspectors, linked to the governance framework.

These variations in governance and coordination directly contribute to the observed regulatory gaps across ASEAN:

Lack of Specific BESS Codes: The absence of dedicated, legally binding BESS installation safety regulations in many of the AMS often correlate with governance structures where the specific mandate or process to develop such detailed, technology-specific codes is unclear or lagging behind market deployment.

Standardisation Gaps: Issues like the lack of clear HV/LV differentiation or specific rooftop PV grounding requirements persist partly because the responsible bodies within the governance structure may not have prioritised or had the capacity to address these specific technical nuances in national regulations or standards.

Inconsistent Application: Weak enforcement mechanisms or fragmented responsibilities directly lead to inconsistent application of existing standards, contributing to safety risks and creating an uneven playing field for developers and investors.

4.5. Comparative Assessment of Regulatory and Standards Adoption

4.5.1. Intra-ASEAN Comparison

A comparison of the national regulatory landscapes detailed in previous sections reveals a wide spectrum of maturity and enforcement regarding PV and BESS electrical safety within ASEAN. A distinct gap exists between AMS with relatively advanced frameworks, and those with nascent or incomplete regulations.

Leaders (e.g., Singapore, Malaysia, Thailand): These countries demonstrate comprehensive approaches, typically featuring national standards (SS 638, MS series/ESAH, EIT/Utility codes) that formally adopt or closely align with core IEC standards for both PV and, increasingly for BESS. They possess clearer institutional mandates (EMA, ST, ERC/Utilities) and more established enforcement mechanisms (LEW systems, utility connection requirements, specific installation codes).

Developing/Partial Frameworks (e.g., the Philippines, Indonesia, Viet Nam, Cambodia): These nations often have formal regulations covering PV installation safety (like the Philippines' PEC 2017, or Indonesia's Permen ESDM), but face major gaps in dedicated BESS safety regulations. Implementation relies more heavily on referencing international standards on a *de facto* basis, often driven by large projects or financier requirements. Enforcement consistency can be a challenge. Recent updates, like Cambodia's 2024 rooftop PV regulations show progress, but highlight the ongoing development process.

Nascent/Gap Frameworks (e.g., Brunei, Lao PDR, Myanmar): These countries without dedicated or specific, codified national safety regulations for PV and BESS often rely on general electrical laws (Brunei Electricity Act, Lao PDR LEPTS), codes of practices, outdated or incomplete grid codes, or the direct application of international standards mandated by external actors (financiers, donors). Enforcement appears particularly reliant on project-specific oversight rather than systemic national mechanisms.

Common Trends & Gaps: Across the region, PV safety standards are generally more developed than those for BESS. There is widespread acknowledgement and reference to IEC standards, but the level of formal adoption, national tailoring, and consistent enforcement varies greatly. The lack of specific BESS installation codes and clear rooftop PV grounding standards is a common technical gap across multiple countries. Furthermore, fragmented responsibilities and limited resources can impede effective regional regulatory oversight and enforcement.

Potential for Common Minimum Standards: The observed divergence highlights an opportunity for the AMS to collaborate toward establishing common minimum electrical safety performance levels. This could involve prioritising:

- **Mandatory Adoption of Core IEC Standards**: Ensuring all countries formally adopt and require compliance with foundational standards like IEC 60364 (LV installations), IEC 61730 (module safety), IEC 62109 (inverter safety), and core BESS safety standards like IEC 62619.
- **Basic Installer Competency**: Implementing baseline requirements for verifying the competency of personnel installing PV and BESS systems, perhaps through basic certification or registration schemes.
- **Essential Safety Features & Verification**: Mandating essential protection devices (e.g., appropriate overcurrent protection, basic disconnect switches, functional grounding) and minimum commissioning checks (e.g., based on IEC 62446-1 Category 1 tests) before system operation. Achieving such baseline alignment could significantly enhance regional safety, particularly in countries currently lacking detailed national codes.

4.5.2. Comparison with International Best Practices (Select Regions)

Comparing the general state of ASEAN PV/BESS safety frameworks against established international benchmarks reveals areas where the region, on average, can strive for improvement:

USA: The National Electrical Code (NEC/NFPA 70) provides highly detailed, legally enforceable installation requirements, updated triennially, with specific articles for PV (Art. 690 mandating AFCI/RSD in many cases) and BESS (Art. 706). NFPA 855 specifically governs BESS installation safety (siting, spacing, fire protection), complemented by UL standards for product/system certification (UL 1741, 9540, 1973) and thermal runaway testing (UL 9540A). The new NFPA 70B standard now mandates electrical equipment maintenance programmes. Enforcement occurs via state/local permitting and inspections.

EU/Germany: Harmonised European Norms (EN), often adopting IEC standards, provide a baseline enforced through CE marking. Germany's VDE application rules (e.g., VDE-AR-E 2510-50 for BESS installation, VDE-AR-N 4105/4110 for grid connection) are highly regarded and often referenced globally as best practices. Robust third-party testing and certification (e.g., TÜV SUD) are integral, and installer competency is often linked to formal training and certification programmes. Emerging EU regulations, like the Battery Passport, will add lifecycle sustainability and safety traceability requirements.

China/South Korea: These nations leverage strong national standards (GB/T, KS) often developed in coordination with industrial policy to support large domestic markets. They have comprehensive standards covering various aspects from components to systems and grid integration.

While leading ASEAN nations incorporate many international standards, the gap emerges primarily in the depth, specificity, and consistent enforcement of national regulations, especially for BESS. Compared to benchmarks, ASEAN generally shows:

- Less widespread adoption of detailed, mandatory installation codes specifically for BESS (few equivalents to NFPA 855 or VDE-AR-E 2510-50).
- Variable enforcement of advanced PV safety features (AFCI, RSD), which are often mandatory in the US/Europe.
- Less mature or non-standardised systems for installer and inspector certification and competency verification, as compared to established programmes in Germany or the US.
- Potentially slower cycles for updating national codes to reflect technological advancements (e.g., grid-forming controls, cybersecurity) and international safety insights.
- Less integration of lifecycle considerations (maintenance, decommissioning) into safety regulations than emerging trends (e.g., NFPA 70B, EU Battery Regulation).

Pathways for ASEAN to reach international levels and to elevate regional safety performance, ASEAN could pursue strategies such as:

Developing/Adopting Comprehensive BESS Codes: Prioritising the creation or formal adoption of detailed national standards for BESS installation safety, drawing heavily from established international models like IEC 62933, NFPA 855, and VDE-AR-E 2510-50.

Strengthening Regulatory & Enforcement Capacity: Investing significantly in training technical staff within regulatory bodies and inspection agencies, ensuring they have the resources and mandate for effective oversight and enforcement.

Establishing Credible Competency Frameworks: Implementing robust, possibly regionally recognized, certification programmes for PV and BESS installers and inspectors to ensure a qualified workforce.

Promoting Agile Standard Updates: Creating more dynamic mechanisms for reviewing and updating national regulations to incorporate technological advancements (e.g., cybersecurity via IEC 62443, grid-forming inverters) and safety best practices learned globally.

Enhancing Regional Collaboration: Utilising ASEAN platforms for structured knowledge sharing on regulatory approaches, enforcement techniques, incident data analysis (where feasible), and adoption of international best practices.

4.6. Forward-Looking Technical and Application Challenges

While foundational standards address component and basic installation safety, the successful and safe integration of PV and BESS across ASEAN necessitates focusing on more advanced technical challenges related to grid interaction and the specific application contexts prevalent in the region. Overlooking these aspects, even if basic standards are met, can lead to significant operational failures, grid instability, and safety incidents, undermining the reliability and sustainability of the RE transition.

4.6.1. Grid Integration & Protection Coordination

As PV and BESS penetrations increase, their interaction with the grid becomes a critical safety and reliability consideration. Addressing these technical challenges is vital, not just for the safety of the individual PV/BESS asset, but for the stability and security of the entire power system. Failure can lead to cascading outages, widespread equipment damage, and compromised energy security. Key challenges include:

Impact on Grid Stability and Dynamics: High shares of IBRs significantly reduce overall power system inertia as compared to traditional synchronous generators. This reduced inertia makes the grid more susceptible to rapid frequency deviations following disturbances. Furthermore, voltage stability can be challenged by the intermittent nature of PV generation and the complex power flow patterns introduced by BESS charging/discharging.

These stability issues can lead to violations of grid operational limits without adequate controls, potentially triggering under-frequency load shedding or even system collapse (blackouts). Ensuring IBRs provide grid support functions (e.g., Fast Frequency Response, Synthetic Inertia, voltage support via dynamic reactive power control, potentially using grid-forming inverter capabilities) and possess robust ride-through capabilities (HVRT/LVRT) is essential for maintaining a reliable power supply as the generation mix changes. Standards like IEEE 1547 are evolving to mandate such capabilities, but ensuring compliance across diverse and sometimes weaker ASEAN grids requires careful planning and investment. If the PCS is not adequately designed, the risk of equipment damage, such as BESS failure due to reverse currents during HVRT events, also underscores the need for robust integration standards.[38],[39]

Altered Fault Conditions & Protection Coordination: IBRs behave differently during grid faults when compared to synchronous generators, typically contributing lower fault current magnitudes, but potentially higher harmonic content. This change can “blind” existing grid protection systems designed for traditional power flows.

Protection systems that fail to detect or correctly isolate faults involving IBRs can lead to prolonged fault conditions, increasing the risk of equipment damage (including fire) and posing safety hazards to personnel.

Conversely, overly sensitive protection might cause nuisance tripping of large PV or BESS plants during minor disturbances, impacting grid reliability. Accurate system modelling, updated protection relay settings, and potentially new protection schemes are required for safe coordination, demanding significant technical expertise from utilities and system operators throughout ASEAN.

Cybersecurity Vulnerabilities: The increasing digitalisation and network connectivity of smart inverters, BMS, EMS platforms, and utility SCADA systems create potential vulnerabilities. Successful cyberattacks could manipulate PV/BESS operations causing physical damage (e.g., initiating thermal runaway by overriding BMS safety limits), intentionally destabilising the grid (e.g., by coordinated tripping or voltage manipulation), compromising sensitive operational data, or hindering emergency response.

Ensuring adherence to relevant cybersecurity standards (e.g., IEC 62443 series applied to the Operational Technology-OT environment) and best practices for network segmentation, access control, and monitoring is crucial for maintaining both physical safety and grid security, an area potentially lagging in conventional electrical safety regulations.[40]

4.6.2. Safety for Specific ASEAN Applications

Applying generic international standards without considering the specific environmental and deployment contexts common in ASEAN can lead to unforeseen safety risks and reduced system lifespan. Focusing on these application-specific challenges is essential for ensuring the deployed systems are genuinely safe, durable, and effective in the local environment, preventing costly failures and building long-term confidence in these technologies within the region.

Floating Solar (FPV): While addressing land scarcity, FPV introduces unique risks compared to ground-mount systems. Designing robust and durable mooring/anchoring systems to handle dynamic loads from wind, waves, and water level variations; ensuring long-term integrity of floating structures and electrical components under constant water exposure (corrosion, UV degradation, potential water ingress); safely managing complex, flexible, and waterproof cabling systems; preventing environmental impacts like chemical leaching; ensuring safe maintenance access.

Mooring or structural failures can lead to catastrophic system damage and potential electrical hazards over water. Cable or enclosure failures can cause short circuits or electrocution risks in an aquatic environment. Material degradation or leaching can harm local ecosystems. Addressing these issues requires specific design guidelines and material standards beyond typical PV requirements.

Climate & Environmental Resilience: ASEAN's tropical climate presents significant challenges that standard assumptions might not cover. Persistent high ambient temperatures accelerate component degradation, especially BESS, increasing thermal runaway risk if cooling is inadequate, and reducing energy yield. High humidity and driving rain increase the risks of insulation breakdown, corrosion, and water ingress into enclosures (a documented cause of BESS fires). Frequent and intense lightning necessitates advanced surge protection and highly effective grounding systems. Typhoon-prone regions require structures designed for extreme wind loads.

Failure to design for these specific conditions leads to drastically reduced system lifespan, unexpected failures (fires, electrical faults, structural collapse), and poor economic performance. Climate resilience must be explicitly integrated into the region's safety standards and design practices.

Urban Rooftop Density: Concentrating PV and BESS installations on rooftops in densely populated urban areas demands heightened attention to safety. The consequences of fire incidents are more severe due to the close proximity of occupants and neighbouring properties, the potential for rapid fire spread across interconnected rooftops, and restricted access for firefighting efforts. These access limitations can delay extinguishment and increase risks to emergency responders—a concern underscored by recent incidents in Singapore and Malaysia.

Effective fire prevention (quality installation, AFCI) and mitigation/response strategies (RSD for firefighter safety, non-combustible materials, clear access routes) are non-negotiable in these high-impact environments to protect lives and property.

Off-Grid and Rural Systems: These systems, critical for energy access, operate under different conditions. Often installed with less stringent oversight, may use lower-cost components, face limited access to skilled maintenance, operate without the stabilising influence of a large grid, and may experience harsher environmental conditions.

Ensuring safety and reliability in these contexts requires robust, simple-to-maintain designs, quality components appropriate for the environment, and potentially simplified safety standards or guidelines tailored for rural energy practitioners to prevent hazards and ensure long-term operational success.

Chapter 5

Future Directions and Recommendations

This report has systematically examined the electrical safety landscape for rooftop PV and BESS within ASEAN. We defined core safety principles, identified fundamental hazards like electric shock (especially from persistent DC voltage), arc faults (a major fire risk), and BESS thermal runaway, detailed system architectures and specific mitigation measures, analysed safety incidents highlighting common failure points like poor installation quality and component failures, and assessed the existing regulatory frameworks and standards across the region.

This assessment revealed varying maturity levels, highlighting significant gaps in specific regulations (especially for BESS installation safety detailing thermal/chemical risk mitigation and specific rooftop grounding/lightning protection requirements), enforcement capacity, and harmonisation across the AMS.

Simultaneously, the technological landscape is rapidly evolving. Trends toward digitalisation are enabling a shift from purely **passive protection** (fuses, breakers) to **active safety** paradigms leveraging real-time monitoring, diagnostics, and control. Increasing system complexity (higher voltages, larger capacities, hybrid PV-BESS-EV systems, modular BESS) introduces new challenges. Furthermore, advanced grid-support functions like grid-forming control, while crucial for grid stability, requires updated standards for safe integration. These trends necessitate standards and safety practices that evolve to incorporate considerations like advanced diagnostics, cybersecurity for connected systems, and holistic safety frameworks.

As ASEAN accelerates the deployment of PV and BESS, ensuring robust electrical safety is necessary for protecting lives and property, building the necessary public and investor confidence for sustained growth, maintaining grid stability amid higher renewable penetration, and ultimately achieving a successful and sustainable regional energy transition. This chapter consolidates the findings and proposes expanded, actionable recommendations for future directions, focusing on strengthening regulatory frameworks, advancing technical standards to embrace new safety approaches, enhancing stakeholder collaboration and capacity, and prioritising research relevant to the ASEAN context. A summary of these recommendations is provided in Table 5-1.

Table 5-1 Recommendations for Enhancing Electrical Safety of Rooftop PV and BESS

Category	Key Recommendations
Regulatory Frameworks & Harmonisation	Formally adopt foundational IEC standards (PV & BESS safety, installation, grounding) as mandatory baseline in all AMS Establish common minimum safety benchmarks (protection, disconnects, commissioning tests) Develop/mandate comprehensive national BESS installation codes (addressing thermal/ chemical risks, siting, fire/explosion protection) Address gaps in specific rooftop PV grounding/lightning protection standards Strengthen regulatory capacity and enforcement mechanisms Promote regional harmonisation via common standards/framework
Technical Standards & Best Practices	Embrace and standardise Active Safety concepts (real-time monitoring, diagnostics, self-control) Promote/standardise advanced diagnostics (I/V/R/T, MPPT-level diagnosis, SSLD, AFCI, terminal temperature monitoring, MLPE) Mandate proven safety technologies: RSD and certified DC AFCI Update standards for emerging tech: Grid-Forming inverters, Cybersecurity (per IEC 62443), new battery chemistries, hybrid/modular systems Tailor standards for ASEAN context: Climate resilience (heat, humidity, lightning, typhoons), scale/voltage differentiation, specific applications (FPV, urban density, rural/off-grid) Require CBM protocols driven by monitoring data.

Stakeholder Collaboration, Capacity Building & Awareness	Nationally strengthen formal inter-agency and public-private coordination mechanisms Implement standardised training and mandatory certification/licensing for installers, inspectors, designers, etc Facilitate technical knowledge exchange and develop local testing/certification facilities Launch public awareness campaigns on safety importance and qualified professionals Implement market incentives rewarding adoption of high-safety standard systems and features.
Research & Development	Prioritise R&D on component performance/durability in the ASEAN climate Develop cost-effective safety solutions for rural/off-grid contexts Improve DC AFCI reliability and BESS failure prediction algorithms Research safer materials for components.

5.1. Regulatory Frameworks and Harmonisation

Effective governance and clear, enforced regulations are the bedrock of electrical safety. The variations identified in Chapter 4 necessitate targeted actions:

Adopt Foundational Standards and Minimum Benchmarks: Chapter 4 identified several AMS lacking specific, codified national safety regulations for PV and BESS, leading to reliance on project-specific requirements or potentially unsafe practices. Establishing a mandatory baseline is essential.

Recommendation #1: The AMS currently lagging (e.g., Brunei, Lao PDR, Myanmar) should prioritise the formal adoption and enforcement of foundational international IEC standards as legally binding minimum requirements. Key standards identified throughout this report include: IEC 60364 series (esp. Part 7-712 for PV installations, Part 5-54 for Earthing), IEC 61730 (PV module safety), IEC 62109 (Inverter safety), IEC 62619 (Industrial Li-ion battery safety), and the IEC 62933 series (esp. Parts 5-1 General Safety & 5-2 Electrochemical Safety for BESS). This ensures a common technical language and minimum safety level.

Recommendation #2: Define and mandate common minimum safety benchmarks across ASEAN for all installations. This should include fundamentals discussed in Chapter 3: effective equipment grounding and equipotential bonding; appropriately rated DC and AC overcurrent protection (e.g., gPV fuses per IEC 60269-6); accessible and clearly labelled disconnect switches for safe isolation; basic BESS thermal management considerations (even if rudimentary ventilation); adherence to essential commissioning tests (e.g., visual inspection, polarity, insulation resistance per IEC 62446-1 Category 1); and provision for basic emergency shutdown.

Close Specific Regulatory Gaps: Even where some PV regulations exist, Chapter 4 highlighted major gaps concerning BESS installation safety specifics and rooftop PV grounding, areas linked to significant global incidents.

Recommendation #3: The AMS with partial frameworks (e.g., the Philippines, Indonesia, Viet Nam, Cambodia) must develop and enforce comprehensive national codes specifically for BESS installation safety. These codes must go beyond general references to IEC 62933 and incorporate detailed, prescriptive requirements derived from international best practices (e.g., NFPA 855, VDE-AR-E 2510-50) covering: safe siting (separation distances), container/room ventilation design, validation of thermal management effectiveness (potentially referencing UL 9540A testing), specific fire detection and suppression system requirements (appropriate agents, coverage), explosion control/venting measures, and safe integration/commissioning procedures.

Recommendation #4: National electrical codes across ASEAN must explicitly address the lack of specific rooftop PV grounding and lightning protection standards. This involves developing clear requirements for grounding electrode systems suitable for rooftop environments, robust equipotential bonding of all metallic components (modules, racking, enclosures), and the specification, installation, and testing of SPDs on both DC and AC sides, considering the high lightning flash density in the region (referencing IEC 62305 principles). This addresses risks identified in incidents like the Indonesian lightning strike case.

Enhance Enforcement and Governance: Regulations are ineffective without proper enforcement, which Chapter 4 identified as varying levels of implementation across the region.

Recommendation #5: Empower national energy regulators or relevant safety authorities with clear legal mandates, adequate technical expertise (through training), and sufficient resources to conduct effective oversight, inspections, and enforcement actions related to PV/BESS safety. Additionally, strengthen enforcement mechanisms. This can include mandatory safety checks before utilities approve grid connection approval, incorporating compliance into building permits issued by local governments (like the Philippines' OBO enforcing PEC), random site audits, and penalties for non-compliance.

Promote Regional Harmonisation: Regulatory divergence hinders trade, increases costs, and can lead to inconsistent safety levels across ASEAN. Harmonisation facilitates market growth and shared learning.

Recommendation #6: Actively work towards a unified ASEAN Electrical Safety Code framework or, more pragmatically, an agreed-upon set of common minimum standards and technical requirements based on international norms (IEC/IEEE). This provides predictability for investors and manufacturers.

5.2. Technical Standards and Best Practices

Advancing technical standards and best practices must evolve beyond minimum compliance to incorporate technologies and practices that proactively enhance safety.

Embrace Active Safety and Advanced Diagnostics: Traditional passive protection has limitations, particularly in detecting incipient faults or low-level anomalies. Digitalisation enables a proactive approach.

Recommendation #7: Shift the safety paradigm by promoting and standardising active safety systems. Standards should define requirements for systems incorporating self-sensing, self-diagnosis, and automated responses based on real-time data.

Recommendation #8: Promote and standardise the integration of advanced real-time diagnostic monitoring technologies as integral parts of PV and BESS safety systems. This includes specifying requirements for: [8]

- **Comprehensive Parameter Monitoring**: Beyond basic I/V, require monitoring of insulation resistance and component/terminal temperatures (I/V/R/T) to detect degradation and overheating proactively.
- **Precise Fault Location**: Standards for features like MPPT-level insulation diagnosis to pinpoint fault locations quickly and accurately, reducing O&M time and risk.
- **Active DC Protection**: Define requirements for Smart String-Level Disconnection (SSLD) systems to actively detect and isolate DC faults (like reverse polarity or backfeed) that conventional fuses might miss.
- **Intelligent Arc Detection**: Mandate AI-powered DC AFCI systems compliant with IEC 63027 / UL 1699B, and demonstrating high reliability (e.g., CGC L4) for fast (<0.5s), accurate detection over long distances, potentially integrated with MLPE for module-level arc location.
- **Connection Safety**: Require smart terminal temperature monitoring using integrated sensors to detect poor connections before they cause overheating or fires.

- **Module-Level Safety & Diagnostics**: Promote Module-Level Power Electronics (MLPE) where appropriate, standardising their diagnostic reporting and ensuring compliance with module-level rapid shutdown requirements (e.g., NEC 690.12).

Mandate Proven Safety Technologies: Technologies like RSD and AFCI directly address major, documented hazards (DC shock risk to responders, DC arc fires) highlighted in Chapters 2 and 3.

Recommendation #9: Mandate RSD capabilities conforming to recognised international standards (e.g., NEC 690.12, VDE-AR-E 2100-712) for relevant rooftop PV installations (especially on occupied buildings) across all AMS to de-energise arrays quickly for firefighter and maintenance personnel safety. Additionally, mandate certified DC AFCIs (per IEC 63027 / UL 1699B) meeting stringent performance criteria in PV systems to reliably detect and interrupt dangerous DC arcs, a common ignition source.

Address Emerging Technologies and System Complexity: New technologies and larger, more complex systems introduce new interactions and potential failure modes that standards need to cover.

Recommendation #10-1: Update grid codes and interconnection standards to safely integrate Grid-Forming inverters and specify requirements for advanced grid support functions. This includes defining testing procedures, performance validation, and ensuring proper coordination with existing grid protection schemes.

Recommendation #10-2: Integrate mandatory cybersecurity requirements into PV/BESS standards and procurement specifications, using frameworks like IEC 62443 to address vulnerabilities in connected inverters, BMS, and control systems.

Recommendation #10-3: Develop holistic safety frameworks and standards for hybrid systems (PV+BESS+EV charging, etc.), considering the interactions between subsystems, and for modular/mobile BESS addressing transport risks, deployment flexibility, and safe temporary connections.

Recommendation #10-4: Establish agile processes within standards bodies to review and adapt safety requirements for new battery chemistries as they enter the market.

Tailor Standards for ASEAN Context: Generic international standards may not fully account for ASEAN's specific environmental conditions or common application types.

Recommendation #11-1: Develop clear technical guidelines or annexes within national standards that differentiate safety requirements based on system scale (residential vs. C&I) and voltage levels (LV vs. HV).

Recommendation #11-2: Explicitly integrate climate resilience into design and installation standards. Specify appropriate component temperature ratings, corrosion resistance, enhanced IP ratings for enclosures (considering driving rain and humidity), mandatory robust lightning/surge protection strategies, and structural design requirements accounting for typhoon wind loads in relevant areas.

Recommendation #11-3: Create specific safety guidelines or code sections for challenging applications prevalent in ASEAN: FPV (addressing mooring, dynamic cabling, water exposure, maintenance access); dense urban rooftops (focusing on fire spread prevention, non-combustible materials, firefighter access, RSD mandates); and rural/off-grid systems (prioritising robustness, simplicity, ease of maintenance, essential protections suitable for potentially lower oversight levels).

Recommendation #12: Implement condition-based maintenance (CBM) protocols. Data gathered from these advanced monitoring systems should inform maintenance schedules, moving away from purely time-based inspections towards proactive interventions based on actual equipment health. Monitor passive safety components like SPDs.

5.3. Stakeholder Collaboration, Capacity Building, and Awareness

A strong safety culture requires collaboration, competence, and awareness across the entire value chain.

Strengthen Stakeholder Coordination: Fragmented responsibilities hinder effective safety management, as noted in Chapter 4's governance analysis.

Recommendation #13: Establish or strengthen formal national inter-agency committees and public-private platforms dedicated to PV/BESS safety. These should facilitate regular dialogue and coordinated action between ministries, regulators, utilities, standards bodies, safety authorities, industry associations, training providers, and emergency services.

Build Capacity and Ensure Competency: Lack of expertise amongst installers and inspectors is a frequent contributor to safety incidents. The increasing complexity of technology requires continuous upskilling.

Recommendation #14-1: Launch ASEAN-wide or nationally standardised, comprehensive training and certification programmes for all key roles: installers (emphasising code compliance, correct techniques, hazard recognition), inspectors (verification methods, testing protocols), designers (standards application, risk assessment), O&M personnel (preventative maintenance, diagnostics), and emergency responders (PV/BESS specific hazards and tactics).

Recommendation #14-2: Mandate formal training and licensing/certification for PV and BESS installers, potentially tiered based on system complexity, as a prerequisite for practising. This directly addresses installation quality issues.

Recommendation #15: Facilitate technical knowledge exchange and best practice sharing between the AMS with varying levels of regulatory maturity and technical expertise. Support the development of local, accredited testing facilities and laboratories to enable affordable verification of equipment safety and performance against standards within the region.

Promote Public Awareness and Safe Choices: End-user awareness influences purchasing decisions and operational safety.

Recommendation #16: Implement targeted public education campaigns through various channels (media, workshops, utility bills, government websites) to inform consumers and building owners about the benefits of using certified equipment and qualified installers, the importance of regular maintenance, and basic safety precautions.

Recommendation #17: Design and implement market-based incentives (e.g., subsidies, preferential tariffs, tax credits) that are explicitly linked to adherence to high safety standards and the adoption of systems incorporating certified advanced safety features (AFCI, RSD, quality monitoring, certified BESS). This encourages market uptake of safer technologies.

5.4. Research and Development

Targeted R&D can address specific regional knowledge gaps and foster innovation in safety solutions. Regional collaboration should be encouraged.

Recommendation #18: Investigate the long-term performance, degradation mechanisms, and failure modes of PV/BESS components (modules, inverters, batteries, cables, connectors, enclosures) specifically under

ASEAN's prevalent high ambient temperature and humidity conditions to inform material selection and design standards, including the relevance to decommissioning procedures.

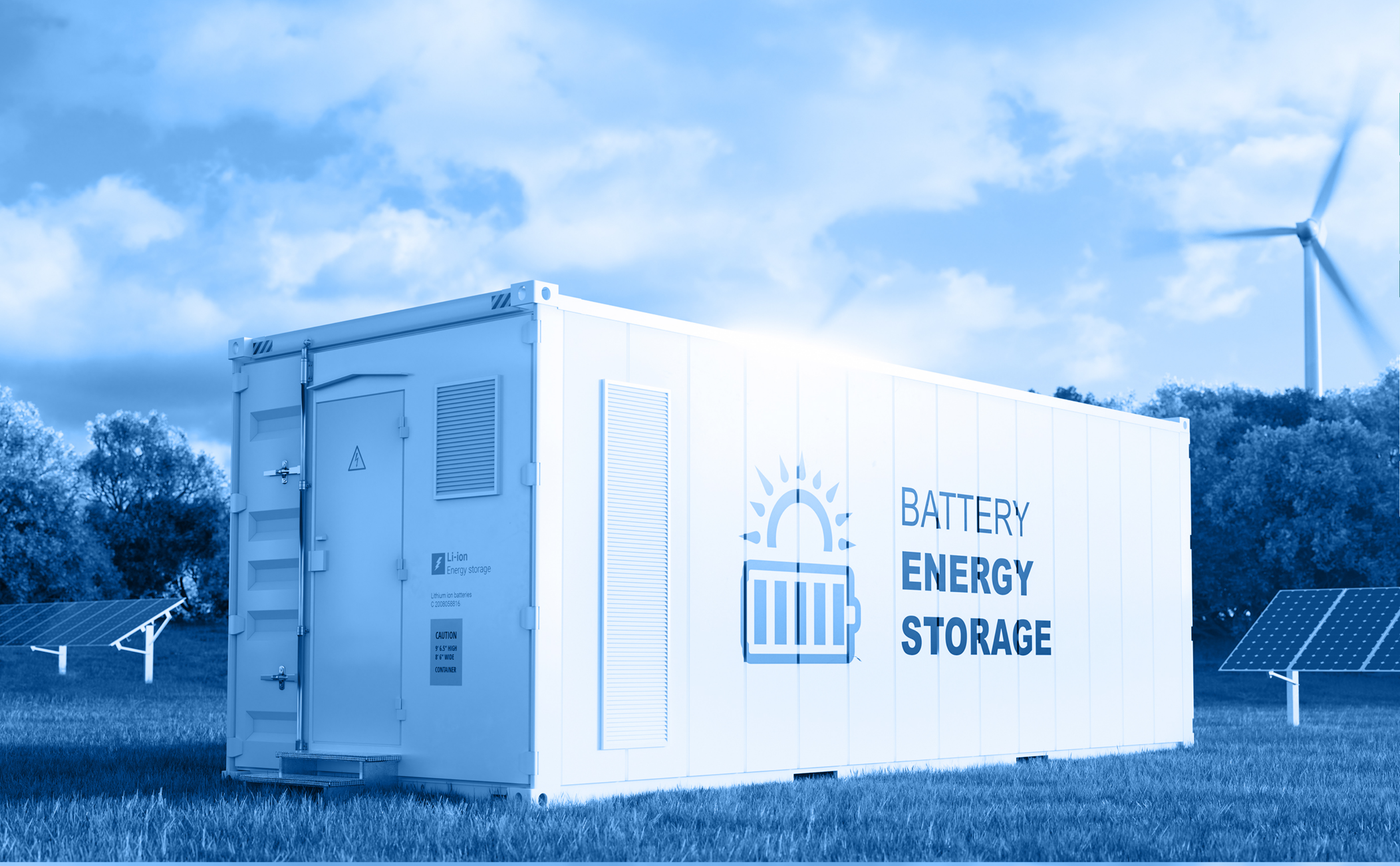
Recommendation #19: Develop and validate cost-effective, robust, and easily maintainable safety components and system designs suitable for widespread deployment in off-grid and rural electrification projects, considering potentially limited maintenance capacity.

Recommendation #20-1: Improve the reliability, accuracy, and noise immunity of DC arc detection (AFCI) technologies, particularly for challenging series arcs in complex or large PV systems common in the region.

Recommendation #20-2: Advance BESS SOH monitoring and early failure prediction algorithms integrated into BMS, capable of detecting subtle precursors to events like internal short circuits or thermal runaway, allowing for timely intervention.

Recommendation #20-3: Advanced SOC calibration should be adopted to avoid imbalance of SOC amongst the cells in the pack which might induce a series of safety issues triggered due to some overcharge and overdischarge on certain cells during operation.

Recommendation #21: Support materials science research focused on inherently safer battery chemistries suitable for tropical climates, improved fire-resistant materials for enclosures, separators, and cabling, and materials that minimise the release of toxic gases during potential failures.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