A gap analysis of technical standards for active safety online monitoring and fire hazards for lithium-ion batteries

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***Abstract*—Lithium-ion batteries are popular energy storage systems with high energy and power densities. However, the considerable heat released during their operation and potential malfunctions pose fire risks, raising safety concerns for energy storage facilities. This paper explores the technical standards for lithium-ion batteries and advocates for the integration of detection technologies for nanoparticles and characteristic gases for batteries monitoring. Factors include nanoparticles, H2, CO, electrolyte volatiles, temperature, and humidity can enable comprehensive online monitoring. Early detection of potential risks allows for timely intervention and elimination, mitigating safety accidents—a crucial consideration in the large-scale construction and application of batteries. Existing standards lack specifications for online monitoring of energy storage safety, encompassing battery management systems (BMS), gas monitoring, particle analysis, and fire warning technologies. The relevant technical standards will be discussed to address the current gaps in battery safety standards, particularly emphasizing the fire detection and warning technologies. There is a need to establish a comprehensive technical standard for the safety monitoring of energy storage, guiding the safe, efficient, and sustainable development of the energy storage industry.**

Keywords*—*Lithium-ion battery, Standards, Active safety online monitoring, Fire early warning, Energy storage.

I. INTRODUCTION

The advent of large-scale energy storage technologies has ushered in a transformative era for diverse sectors, promising innovative solutions to address pressing energy challenges [1]. Large-scale energy storage is poised to play a pivotal role in shaping the future of energy management. From the evolution of smart grids to the realization of smart cities and the integration of renewable energy sources, the applications are multifaceted [2]. Additionally, energy storage is anticipated to underpin the electrification of transportation, support industrial processes, and enhance the resilience of both residential and commercial energy systems. As we delve into the realms of microgrids, emergency preparedness, and grid optimization, the collective impact of large-scale energy storage unfolds, contributing to a more sustainable, efficient, and interconnected energy landscape.

Lithium-ion batteries, with advantages of high energy and power densities, and highly scalable become the most proportionate and fastest-growing form of energy storage [3]. However, improper use of batteries, such as overcharging, over discharging, and overcurrent, can lead to thermal runaway of the batteries, occasionally evolving into combustions in energy storage systems [4]. Since 2017, there have been more than 50 major energy storage fire incidents worldwide with the recent events shown in Table I. Incidents like fires and explosions in energy storage not only cause significant economic losses to enterprises but also exert a considerable impact on the overall industry, resulting in immeasurable losses of manpower, materials, and finances. Real-time online energy storage detection and warning technology, as a cutting-edge and emerging development influencing the future energy landscape, demands comprehensive attention to its safety. Therefore, it is essential to propose more comprehensive and effective

TABLE I: MAJOR FIRE INCIDENTS OF ENERGY STORAGE SYSTEM IN RECENT YEARS GLOBALLY

No.	Time	Location	Case
1	Apr, 2021	Beijing, China	Fire and explosion at an energy storage system, resulting in a direct property loss of over 16.6 million RMB.
2	Apr, 2021	Arizona, United States	Fire in the energy storage facility at the Salt River substation, smoldering for five days.
3	Apr, 2021	Chungcheongnam-do, South Korea	Fire in a photovoltaic energy storage system.
4	Jul, 2021	Victoria, Australia	Fire at Tesla's largest energy storage system.
5	Jan, 2022	Ulsan, South Korea	Fire at SK Energy's battery energy storage building.
6	Feb, 2022	California, United States	Incident at the Moss Landing energy storage project, marking the second incident within six months.
7	Mar, 2022	Taiwan	Accidental fire at the Industrial Technology Research Institute Longjing Energy Storage system.
8	Mar, 2022	Southern Germany	Explosion at a residential battery storage system.
9	Apr, 2022	United States	Fire in the lithium-ion battery energy storage system of the Salt River Project (10 MW).
10	May, 2022	Germany	Explosion at a user-side photovoltaic energy storage system.
11	Jun, 2022	Corsica, France	Fire in a lithium-ion battery storage container at a photovoltaic power plant, causing extensive smoke.
12	Oct, 2022	China	Fire in the energy storage battery room of the Yinggehai Salt Power Plant's 100 MW low-cost photovoltaic project.
13	Sep 2022	United States	Fire in Tesla's Super Battery Energy System at the Pacific Gas and Electric Company's battery storage project.

guidelines for the safety management of lithium-ion battery. It is necessary to compare and summarize existing safety guidelines for energy storage, clarify the challenges and critical points of current technical guidelines, and research and determine the improvement direction of these technical guidelines.

The safety considerations inherent in the deployment of lithium-ion batteries are intricate and involve a spectrum of factors ranging from the battery characteristics to external influences, operational surroundings, and management systems (shown as Fig.1). The battery component, possessing a substantial energy reservoir, raises concerns related to potential defects during production, performance deterioration with age, and the prolonged non-uniformity of the State of Charge (SOC). External perturbations, such as electric surges and external short circuits, amplify risks by inducing insulation failure, thermal shocks, and the diffusion of cells post-thermal runaway incidents.

Operational environments present distinct challenges as meteorological conditions particularly strong winds and sand can elevate working temperatures through the impact on the dust accumulation system in the energy storage setup. Management system-related issues further compound safety risks, encompassing quality defects, non-standard installation and commissioning processes, design inadequacies, and insufficient insulation performance. Human-induced errors during operation or improper site disposal add an additional layer of complexity.

In the context of large-scale construction and application of lithium-ion energy storage, prioritizing safety emerges as the paramount concern. Urgency is underscored in establishing a comprehensive safety monitoring technical standard tailored for energy storage systems. Such a standard would not only address the identified safety challenges but also provide guidance for the industry's secure, efficient, and sustainable development.

II. SCOPE AND PURPOSE OF TECHNICAL STANDARD

The pragmatic dimensions of this standard encompass the utilization of technical terminology, aimed at aiding diverse stakeholders in evaluating the feasibility of safety measures and early warning systems. It further addresses constraints, improvement processes, and the need for additional research and development across various

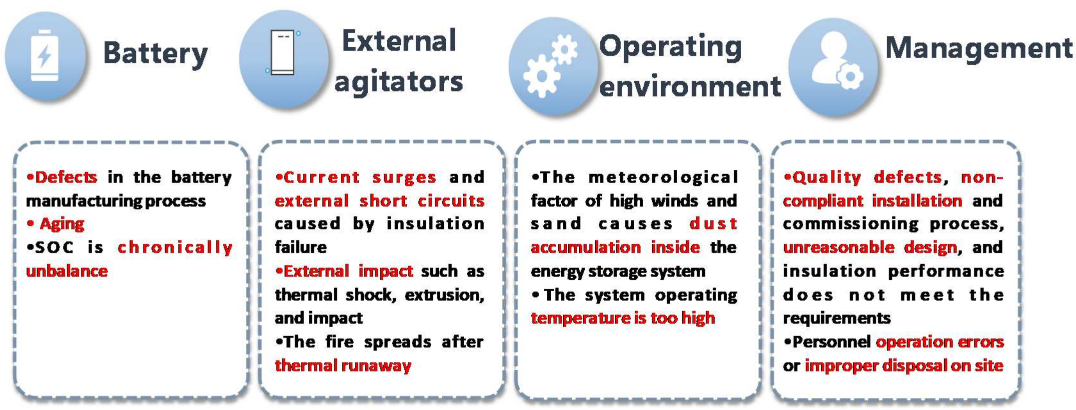

Fig. 1. Factors related to safety hazards of large-scale lithium-ion batteries.

lithium-ion battery energy storage technologies. This initiative is propelled by the escalating demand for energy storage solutions and the imperative to avert disasters, notably fire incidents. The overarching objectives and intent of the standard project are delineated as follows:

A. Scope

Integrating the detection technology of nanoparticles and characteristic gases into parameters such as nanoparticles, H2, CO, electrolyte volatiles, temperature and humidity in the energy storage prefabrication cabin into the monitoring standards of energy storage, achieving comprehensive online monitoring, early detection of latent issues, early warning, and reserving sufficient time for disposal and elimination to avoid safety accidents.

B. Purpose

Two key areas are envisioned to be covered in this new standard as follows:

1) Propose various indicators of active safety monitoring or early warning: To realize active safety online monitoring and fire early warning of energy storage, it is first necessary to clarify the content of monitoring indicators, including battery management system, gas monitoring, and particulate matter detection.

2) To improve the operation level of energy storage in active safety: Standardize the specific technical parameters or scope, test methods and testing rules that should be reached by the relevant indicators of active safety detection and early warning.

III. Related Technical Standards

The burgeoning field of energy storage has become a linchpin in addressing the dynamic energy landscape, offering transformative solutions to enhance efficiency, resilience, and sustainability. As the demand for energy storage technologies escalates, ensuring their safety and reliability is a critical factor, prompting the development of rigorous safety standards and regulations. This imperative has catalyzed a concerted effort among governments, industry enterprises, scientific research institutions, and standardization organizations globally to establish a robust standard for energy storage safety. This section delves into the intricate tapestry of safety standards and regulations governing energy storage, shedding light on the multifaceted contributions of influential international and national organizations that collectively shape the trajectory of safety standards in this critical domain.

A. Relevant standards and regulations organizations

Safety standards and regulations for energy storage have emerged as a focal point of significant attention and consideration among diverse stakeholders, encompassing governmental bodies, industry enterprises, scientific research institutions, and standardization organizations [5]. The landscape of standards development is shaped by prominent international technical organizations, including the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), and the Institute of Electrical and Electronics Engineers (IEEE). Furthermore, influential entities such as the American Fire Protection Association (NFPA), the American Insurer Test Institute (UL), and the German Technical Supervision Association (TuV) significantly contribute to the formulation of technical regulations (shown as Fig. 2).

The ISO is primarily engaged in overseeing standards related to electric vehicle power battery packs, addressing crucial aspects such as performance and safety. Meanwhile, the IEC is instrumental in the global research and development of standards concerning electrical energy storage systems, covering diverse facets ranging from terminology and definitions to safety and environmental issues. IEC/TC120, established in late 2012, is at the forefront of developing global standards for electrical energy storage systems and components, with a structure consisting of five working groups and one joint working group, shown as Table II. Notably, the NFPA assumes a pivotal role in crafting safety operation and emergency response standards for the design, installation, and utilization of energy storage systems, including comprehensive safety standards such as NFPA 855 and UL9540. The IEEE, through its SCC21 Standard committee, focuses on standardization research across various fields, including fuel cells, distributed energy, photovoltaic, and energy storage.

In the United States, the Department of Energy (DOE), spearheaded by the DOE Sandia National Laboratories, collaborates with entities like NFPA, IEEE, and UL to develop a roadmap for energy storage safety standards. This collaborative effort involves revising relevant standards and addressing various aspects of energy storage systems, including building environment, fire protection,

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installation, grid connection, and testing. These standards cover both general electrical safety requirements and those specific to energy storage batteries.

In Germany, safety standardization efforts are primarily associated with organizations such as TuV and the German Association of Electrical Engineers (VDE), both of which have a long-standing history and global recognition. In China, the National Electric Energy Storage Standardization Technical Committee (SAC/TC550) plays a pivotal role in establishing a comprehensive standard system that encompasses planning, design, construction, acceptance, operation, maintenance, overhaul, equipment, testing, safety, environmental protection, and technical management.

These international and national standardization organizations collectively contribute to the development and implementation of safety standards, ensuring the secure, efficient, and sustainable evolution of energy storage systems on a global scale.

Fig. 2. Example of standards and regulations organizations that participate in Li-ion batteries safety and performance monitoring.

TABLE II: THE WORKING RANGE OF IEC

IEC/TC120 working range	Scope of standard development work
WG1	Terms and Definitions
WG2	Energy storage unit parameters and test methods
WG3	Planning and Installation
WG4	Environmental issues
WG5	Security Issues
JWG10 Joint working group with IEC TC8	The distributed generation is connected to the grid

B. Analysis of relevant technical guides

The standards related to energy storage can be classified into various categories as shown in Table III, each addressing specific aspects of safety, lithium-ion battery safety, thermal runaway testing, system installation, and stationary electrical energy storage systems. It is worth mentioning that the standards can cover more than one area.

GB/T 36276-2018 establishes specific safety requirements for lithium-ion batteries used in energy storage, covering aspects such as overcharge, over discharge, insulation, voltage resistance, short circuit, extrusion, drop, and thermal runaway. These regulations provide standards for evaluating the safety of energy storage systems and minimizing the risk of potential hazards during operation.

a) Safety related guides for lithium-ion batteries: Lithium-ion battery safety standards, exemplified by IEC 62619 (2022), are designed to address the unique challenges associated with these batteries. IEC 62619 focuses on safety requirements for lithium-ion batteries and battery packs used in industrial equipment. It proposes safety tests for battery use and environmental applicability, covering aspects such as external short circuit, impact, drop, heat abuse, overcharge, forced discharge, internal short circuit, and thermal runaway spread. The standard ensures the batteries meet specific electrical safety and electromagnetic compatibility requirements.

b) Test method for thermal runaway of energy storage: Thermal runaway test standards, exemplified by GB/T 36276-2018 and UL 9540A (2018), are critical for evaluating the response of lithium-ion batteries to extreme conditions. GB/T 36276-2018 concentrates on detecting thermal runaway in lithium-ion batteries for energy storage, assessing safety at the cell and module levels. UL 9540A evaluates the thermal runaway characteristics of battery energy storage systems, examining explosive gas release during a fire. These standards are essential for understanding the behavior of batteries under adverse conditions, contributing to improved safety measures.

c) Stationary energy storage system installation guide: VDE-AR-E 2510-2 (2021) and VDE-AR-E 2510-50 (2017) focus on safety testing for lithium-ion batteries used in energy storage. VDE-AR-E 2510-2 detects whether lithium-ion batteries used for energy storage pose a risk of catching fire or exploding during thermal runaway. VDE-AR-E 2510-50, a comprehensive safety assessment standard, covers various safety risks in energy storage systems, including electrical safety, battery safety, electromagnetic compatibility, functional safety, and more. These standards collectively contribute to the safe deployment and operation of electrical energy storage systems.

d) Fire detection and alarm: Enhanced fire detection in energy storage requires tailoring systems to diverse fire characteristics. Research in electrochemical storage investigates critical combustion conditions, analyzing parameters including temperature and gas composition during thermal runaway. Establishing characteristic thresholds enables the assessment of

TABLE III: RELEVANT TECHNICAL STANDARDS

No.	Standard No.	Details
Safety related guides for electric energy storage systems		
1	GB/T 36276-2018	Specifications, technical requirements, test methods, and test rules for lithium-ion batteries for electrical energy storage [6]
2	GB/T 36558-2018	General technical conditions for electrochemical energy storage systems in power systems [7]
3	GB/T 34120-2017	Technical specification for energy storage converters for electrochemical energy storage systems [8]
4	GB/T 34131-2017	Technical specification for lithium-ion battery management systems for electrochemical energy storage [9]
5	GB/T 42288-2022	Safety regulations for energy storage [10]
6	GB/T 40090-2021	Operation and maintenance regulations for energy storage [11]
7	IEC TS 62933-5-1: 2017	Electrical energy storage (EES) systems - Part 5-1: Safety considerations for grid-integrated EES systems - General specification [12]
8	IEC 62933-5-2: 2020	EES systems - Part 5-2: Safety requirements for grid-integrated EES systems - Electrochemical-based systems [13]
9	IEC 62933-5-3	EES systems - Part 5-3: Safety requirements for electrochemical based EES systems considering initially non-anticipated modifications-partial replacement, changing application, relocation and loading reused battery [14]
10	IEC 62933-5-4	EES systems - Part 5-4: Safety test methods and procedures for grid integrated EES systems-Lithium-ion battery-based systems [15]
Safety related guides for lithium-ion batteries		
1	IEC 62619:2022	Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries, for use in industrial applications [16]
2	IEC 63056:2020	Corrigendum 1 - Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries for use in electrical energy storage systems [17]
Test methods for thermal runaway of energy storage		
1	GB/T 36276-2018	Lithium-ion batteries for energy storage [6]
2	UL 9540: 2020	Energy storage systems and equipment [18]
3	UL 9540A: 2018	Test method for evaluating thermal runaway fire propagation in battery energy storage systems [19]
4	UL 1973: 2022	Batteries for use in stationary, vehicle auxiliary power and Light Electric Rail (LER) applications [20]
Energy storage system installation		
1	NFPA 855: 2020	Standard for the installation of stationary energy storage systems [21]

severity and guides the selection of suitable detection methods, aiming for a sophisticated early warning system for precise and effective fire detection.

C. *Requirement Analysis*

Current energy storage technology grapples with three pivotal issues: the limited scope of Battery Management

Systems (BMS) confined to battery units, the disjointed and non-targeted monitoring of conventional electrical equipment, and the passive and offline nature of existing fire protection measures. The novel approach establishes new standards and indicators for online monitoring and early warning technology. The envisioned early warning technology as shown in Fig. 3. is designed to exert control over scenarios preceding accidents, encompassing aspects like battery thermal runaway, equipment overheating, and emissions. It emphasizes early detection of security risks to facilitate timely intervention and mitigate potential dangers such as thermal runaway diffusion and fireworks. Traditional emergency responses following accidents are also addressed, covering equipment damage, fire incidents, and potential casualties. Novel online monitoring system employs active inhalation and 24-hour cyclic sampling, utilizing various test technologies including particle analysis, characteristic gases measurement, volatiles tracking, and assessing temperature and humidity levels. To enhance robustness, the system incorporates anti-interference measures to combat external factors like dust, oil mist, water mist, and fog. The new standard aims to significantly advance the efficacy, range, and adaptability of monitoring and early warning systems within the domain of energy storage technology.

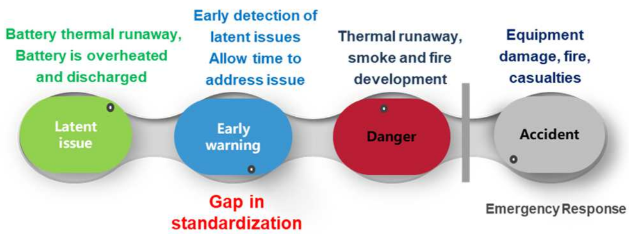

Fig. 3. Processes of early warning technique for lithium-ion battery hazards.

IV. CONCLUSION

This paper presents an overview of technical standards for lithium-ion batteries with a focus on safety monitoring and fire hazards detection. Several energy storage hazards and accidents still happen in recent years. Most of the standards about energy storage safety are related to fire protection, including the use of fire elimination equipment and emergency treatment methods. However, these standards rarely discuss the use of battery management system, fire early warning technology, gas monitoring, particle analysis, and other parameters for energy storage safety online monitoring. This paper introduces the processes of early warning detection techniques. Future work includes to the establishment of an IEEE standard working group to address this standard gap.

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