Exploring the Whole-Process Fire Safety System for Charging Stations

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Abstract. Driven by the dual carbon goals, China has witnessed a rapid expansion of charging stations as critical supporting infrastructure for new energy vehicles. However, fire incidents caused by battery thermal runaway and electrical failures have exposed vulnerabilities in their fire safety protocols. To address issues such as the lack of differentiated risk assessment, incomplete whole-process safety mechanisms, and poor coordination between technical and managerial measures in existing research, this study focuses on the diverse operational scenarios of charging stations. It systematically examines fire risk definitions and typologies, analyzes safety concerns across all stages, and establishes a comprehensive fire safety framework covering pre-incident, during-incident, and post-incident phases. The research identifies risk variations among different types of charging stations, pinpoints safety challenges at each stage, and proposes integrated technical-managerial solutions featuring precise pre-incident risk assessment and early warning, semi-automated during-incident response, and post-incident emergency protocols. This framework provides systematic technical support for the safe operation of charging stations, contributing to the sustainable development of the new energy vehicle industry.

Keywords: Charging station, Fire safety, Dual carbon goals, Whole-process safety

1 Introduction

Under the guidance of the dual carbon strategic goals, the new energy vehicle industry has become a core driver for energy structure transformation and green development [1]. As critical supporting infrastructure, charging stations are experiencing exponential growth. By the end of 2024, China's total number of charging facilities reached 12.818 million units, representing a year-on-year increase of 49%. The annual charging volume exceeded 110 billion kWh, with a growth rate of 38% compared to the previous year.

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However, the rapid expansion and increasing technological diversity of charging stations have amplified safety risks and potential hazards. In April 2021, a fire and explosion occurred at an integrated solar-storage-charging project in Beijing, resulting in one fatality, two firefighters losing their lives, and one firefighter injured. The direct property loss amounted to 16.6081 million RMB [2]. The incident involved two brick-concrete buildings: the North Building and the South Building, with an underground outdoor cable trench connecting them. The direct cause of the fire in the South Building was an internal short circuit in a lithium iron phosphate battery within the western battery room, which led to thermal runaway and ignited the battery. The explosion in the North Building was directly triggered by an internal short circuit in a single lithium iron phosphate battery in the South Building's battery room. This caused thermal runaway that spread to the battery modules, igniting a fire. Flammable and explosive components produced by the incident entered the energy storage room of the North Building through the cable trench, mixed with air to form an explosive gas, and ignited upon contact with an electrical spark. As energy-intensive hubs involving multiple risks including battery thermal runaway and electrical failures, the fire safety of charging stations is crucial for both the sustainable development of the new energy vehicle industry and fundamental public safety. Establishing a robust and scientifically grounded prevention and control framework has therefore become an urgent priority [3].

Existing research on charging station fire safety has achieved certain progress. Technically, scholars have conducted explorations in areas such as battery thermal runaway monitoring and fire suppression equipment development, leading to the creation of technical products like multi-parameter sensors and specialized extinguishing agents [4-5]. On the management front, preliminary safety standards and operational guidelines have been established. However, significant limitations remain in current research. Firstly, risk assessments often follow a one-size-fits-all approach, lacking tailored analysis for the distinct risks associated with different station types such as unattended stations, photovoltaic-integrated storage stations, and comprehensive energy stations. Secondly, prevention technologies tend to focus on isolated stages rather than forming a holistic system covering the pre-incident, during-incident, and post-incident phases. Additionally, there are issues with equipment compatibility and integration into real-world scenarios. To address these fragmented approaches, this study builds upon the diverse characteristics of charging station scenarios. With a core focus on whole-process safety management, it aims to construct a fire safety system that integrates risk assessment and early warning, semi-automated response, emergency measures, and systemic coordination. The objective is to provide systematic support for the safe development of charging stations.

2 Definition, Typology, and Incident Analysis of Fire Risks in Charging Stations

2.1 Definition and Classification

Fire Safety Risk in Charging Stations refers to a comprehensive representation of both the likelihood and severity of potential adverse outcomes—such as personal injury, property damage, environmental harm, and energy supply disruption—resulting from fire incidents during the operational lifecycle of a charging station. These risks may arise from internal equipment defects, anomalies in energy interaction processes, external environmental interference, or deficiencies in management mechanisms. Rooted in the characteristics of multi-energy coupling and intensive equipment operation, such risks involve various risk carriers including electrical systems, energy storage units, and photovoltaic components, and exhibit distinct features depending on the type of charging station.

From a typological perspective, charging station risks can be categorized multidimensionally based on their causes and operational contexts. For unattended charging stations, primary risks include electrical failures due to equipment aging, delayed detection of initial hazards caused by remote monitoring gaps, and human factors such as improper third-party operations. PV-integrated storage charging stations face distinctive challenges, such as combustion of EVA encapsulant films and back sheets in photovoltaic modules, thermal runaway of lithium-ion storage batteries, and electrical compatibility issues arising from the coordinated operation of solar and storage systems. Integrated energy stations, which combine services like charging, energy storage, and fuel supply, exhibit compounded risks. In addition to conventional electrical fire hazards, they are susceptible to secondary disasters triggered by interactions between different energy mediums. Common risks across all station types include electrical failures like DC arcing, cable overloads, and cooling system failures, along with external risks induced by extreme weather or physical impact.

2.2 Incident Analysis

Fire incidents at charging stations typically exhibit three key characteristics: multiple contributing factors, rapid escalation, and cascading consequences. Their progression patterns vary considerably depending on the station's configuration. In terms of root causes, battery thermal runaway and electrical failures are the two primary triggers. Battery thermal runaway is commonly initiated by internal short circuits, overcharging, over-discharging, or external thermal abuse. This process releases substantial heat and flammable gases, which can create explosive conditions within a short period. Electrical failures include issues such as insulation degradation and cable overloads. Particularly noteworthy are DC-side electrical arcs, which lack self-extinguishing properties. Once initiated, they can sustain prolonged discharges, rapidly igniting surrounding materials and accelerating fire spread.

Distinct incident patterns emerge across different station types. At unattended stations, the absence of real-time human intervention often allows initial hazards to escalate due to delayed monitoring responses. Equipment aging and improper third-party operations are the predominant causes here. PV-integrated storage stations frequently experience cascading effects, where photovoltaic module combustion triggers thermal runaway in energy storage batteries. The toxic smoke released during component combustion significantly complicates rescue operations. Integrated energy stations, with their multi-energy coupling, are prone to cross-risk propagation. In such setups, a single equipment failure can initiate multi-system chain reactions. External factors such as extreme weather or physical impact often act as catalysts, substantially shortening the transition time from potential hazards to actual incidents.

3 Analysis of Whole-Process Fire Safety Issues

3.1 Pre-Incident Phase

Pre-incident fire safety concerns primarily manifest in three aspects: imprecise risk assessment, delayed monitoring and early warning, and inadequate standardized management. Firstly, risk evaluations often rely on uniform templates without accounting for variations in station types. This approach fails to address specific risks such as remote management blind spots in unmanned stations, coordinated operational risks in photovoltaic-energy storage stations, and multi-energy interaction risks in integrated energy stations, resulting in incomplete hazard identification. Secondly, traditional single-modality sensors used in monitoring systems are prone to environmental interference and high rates of undetected incidents. They struggle to capture early signs of battery thermal runaway, such as subtle temperature increases and minimal gas emissions, as well as precursor indicators of photovoltaic module pyrolysis. Moreover, some stations lack real-time integration between monitoring data and early warning systems. Lastly, risk classification standards tailored to different station types remain underdeveloped. Maintenance protocols often lack systematic hazard inspection mechanisms, particularly in unmanned scenarios where remote operational response times and intervention accuracy fall short of initial risk control requirements, thereby creating latent vulnerabilities for incident initiation.

3.2 During-Incident Phase

Fire safety challenges during active incidents are primarily characterized by delayed response, inadequate equipment adaptability, and failed coordinated control mechanisms. Traditional firefighting heavily relies on manual operations—fire blanket deployment is time-consuming and often misses critical initial response windows, while conventional equipment cannot penetrate battery casings to suppress internal thermal runaway reactions, exhibiting particularly limited effectiveness against fires in concealed areas like vehicle undercarriages. Significant gaps exist in semi-automated suppression systems. Some stations lack automatic fire blankets and mobile specialized firefighting equipment, and even when available, unclear operational procedures undermine their effectiveness. Integrated prevention mechanisms remain underdeveloped: coordinated deployment of fire barriers and high-pressure water mist systems is often insufficiently rapid, hindering swift fire containment in densely configured integrated energy stations. At unmanned sites, the absence of on-site personnel leads to delays in automated equipment activation and system coordination. Furthermore, in high-smoke scenarios, poor synchronization between blanket deployment and water mist application increases risks of fire spread or re-ignition.

3.3 Post-Incident Phase

The current post-accident response phase has revealed several systemic shortcomings in practical operations. The primary issue lies in the gaps within manual rescue intervention mechanisms. When semi-automatic fire suppression systems fail, a lack of standardized protocols for alarm handling, dispatch coordination, and resource allocation leads to delayed responses from professional firefighting units. Furthermore, unified procedural standards for on-site operations have not been established. Command posts often rely on improvised decisions rather than scientifically-grounded guidelines based on typical accident models when acquiring information, formulating tactics, and deploying resources, which compromises operational efficiency.

The post-fire management phase exhibits significant blind spots in risk control, particularly in the persistent monitoring of secondary hazards such as battery re-ignition and gas leaks, alongside an absence of specialized cleanup protocols. A more pressing concern involves the after-action review mechanism. The current system struggles to integrate automated early-warning data with manual intervention records, preventing a precise analysis of the root causes behind semi-automatic system failures. The lack of quantifiable metrics for evaluating timeliness across all operational stages also hinders the ability of review conclusions to effectively inform preliminary risk assessments and optimize emergency response plans. This ultimately obstructs the closed-loop iteration and continuous improvement of the fire safety ecosystem. These issues highlight systemic deficiencies throughout the entire process, from manual intervention to post-incident analysis, underscoring the urgent need to establish standardized operational frameworks.

3.4 System Coordination

Insufficient coordination within the whole-process fire safety system for charging stations manifests as multi-dimensional disconnections and failed synergies. Pre-incident risk assessments and monitoring mechanisms fail to form a closed loop, with risk classification outcomes not effectively informing adjustments to monitoring systems. The lack of standardized data protocols across different station types undermines cross-site risk analysis. A disconnect exists between pre-incident hazard identification and during-incident equipment deployment, where high-risk areas identified beforehand lack corresponding specialized fire suppression equipment. Unattended stations experience delays in transmitting remote alerts to activate on-site automated systems.

Technical and managerial coordination remains inadequate: maintenance procedures for automated fire prevention equipment are not integrated with routine safety inspections, and advanced monitoring devices in some stations yield unused data due to management gaps. Cross-entity collaboration is particularly weak, with insufficient information exchange between station safety systems and emergency response platforms. Integrated energy stations lack horizontal data sharing among charging, storage, and other subsystems, creating safety blind spots. Furthermore, post-incident review conclusions fail to systematically refine pre-incident risk assessment frameworks, leading to recurring hazards and impeding continuous improvement of overall prevention capabilities.

4 Establishment of A Whole-Process Fire Safety Framework for Charging Stations

The proposed full-process fire safety system for charging stations is illustrated in Figure 1. This framework follows a three-phase structure covering pre-incident, during-incident, and post-incident stages. It begins with multi-source perception monitoring and dynamic risk assessment in the pre-incident phase, progresses to emergency response through integrated platform dispatch of automated firefighting equipment during incidents, and concludes with comprehensive hazard screening and incident review afterwards. The system synergy further emphasizes coordinated operations and closed-loop management, highlighting continuous improvement through upgrades of firefighting equipment and reinforcement of risk point control. Ultimately, this forms a comprehensive security defense system.

4.1 Pre-Incident Phase Framework

The pre-incident phase framework focuses on precise risk prevention, emphasizing the integration of differentiated assessment, intelligent monitoring, and standardized operations. Tailored risk evaluations are conducted based on the characteristics of different charging station types, incorporating the remote management features of unmanned stations, solar-storage coordination risks in PV-integrated stations, and multi-energy interactions in comprehensive energy stations. A dynamic risk classification mechanism is established to enable accurate hazard identification. A multi-source sensing monitoring system integrates hardware such as charging safety modules, infrared thermal imaging probes, fire detection sensors, and smoke detectors to capture real-time dynamic indicators including abnormal charging parameters, elevated temperatures, and gas concentration changes. Intelligent algorithms analyze these data to achieve risk localization and rapid early warnings. Safety standards adaptable to diverse scenarios are refined, specifying monitoring frequencies and operational procedures for different station types. A regularized hazard inspection mechanism is implemented, with enhanced response-time management for remote operations at unmanned stations, thereby reducing the probability of incidents at their source.

The effectiveness of differentiated risk assessment has been validated in real-world scenarios. For instance, Taizhou City's "full-chain remediation" initiative for e-bike safety demonstrated that clarifying accountability boundaries across production, sales, and usage phases significantly reduces systemic risks. From January to April 2025, e-bike fires in the city decreased by 51.1% year-on-year, underscoring the positive impact of precise risk categorization on source control [6]. Concurrently, the implementation of intelligent monitoring requires integration with standardized training. Chifeng City's "on-demand" fire safety training program in the logistics and warehousing sector leveraged VR simulations to conduct targeted drills for operational risks during peak sorting periods, significantly enhancing new employees' ability to identify potential hazards [7]. Such practices demonstrate that aligning risk profiles with training content can compensate for the lack of manual intervention in scenarios like unmanned stations.

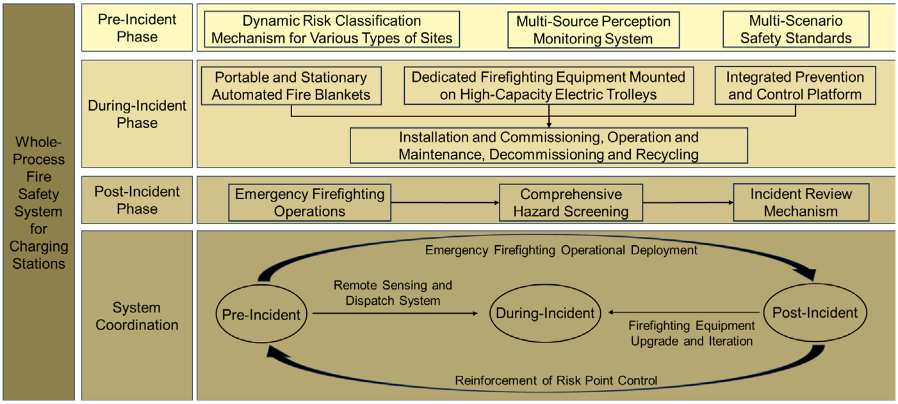

Fig. 1. Framework of the whole-process fire safety system for charging stations.

4.2 During-Incident Phase Framework

The during-incident system framework prioritizes rapid response and precise suppression, centering on semi-automated equipment clusters and multi-dimensional coordination mechanisms. Mobile and fixed automated fire blanket systems are deployed, utilizing elastic potential energy deployment and folding-arm positioning technologies to achieve rapid deployment and precise coverage, significantly reducing initial response time. Specialized firefighting equipment mounted on high-capacity electric carts employs long-range precision nozzles to apply lithium-battery compatible suppressants directly to ignition sources, overcoming traditional equipment limitations in penetrating battery interiors.

An integrated prevention platform combines high-pressure water mist systems with collapsible fire barriers. The wheel-mounted barriers allow flexible deployment, while integrated multi-directional nozzles enable sustained suppression. This system works in tandem with fire blankets to address confined spaces and high-smoke scenarios. Unmanned stations feature enhanced automated activation logic to ensure prompt response without human intervention. For PV-integrated and comprehensive energy stations, equipment activation sequences are optimized to prevent multi-system interference, effectively containing fire spread and re-ignition risks.

Fire response efficiency is highly dependent on the synergy between monitoring and action. The fire protection IoT system deployed by State Grid Gansu Electric Power Company demonstrated this during a fire incident at the Qilian Converter Station, achieving fire alarm verification and remote visual dispatch within 30 seconds. On-site firefighters arrived within 5 minutes, and the blaze was contained within 3 hours through coordinated efforts between enterprise and municipal firefighting teams [8]. This case shows that integrating thermal imaging early-warning technology with semi-automated equipment clusters (such as the automated fire blankets outlined in the framework) can effectively reduce response delays from alarm to action.

4.3 Post-Incident Phase Framework

The post-incident management system must prioritize establishing clear manual rescue intervention protocols. When semi-automatic fire suppression equipment fails to control a blaze, standardized manual rescue procedures should be activated immediately, following the alarm response and dispatch specifications in the overall emergency plan. The fire command platform should utilize multi-source perception systems to receive real-time field data, initiate appropriate resource mobilization plans based on the disaster level, and ensure that professional firefighting units organized according to standardized combat readiness protocols can arrive on-site promptly to execute specialized operations.

On-site firefighting operations must strictly adhere to the standardized workflow of reconnaissance, decision-making, deployment, and action. Upon arrival, the command post should first review automated warning system data combined with physical reconnaissance to confirm critical information such as fire spread patterns and the status of trapped individuals. Tactical plans should then be developed according to the specific risks characteristic of charging stations, incorporating key technical points from typical accident response models. Finally, specialized forces and equipment, including vehicle-mounted monitors and portable firefighting units, should be deployed systematically based on established combat formation standards.

After extinguishing open flames, the process should transition to a systematic post-fire management phase focusing on comprehensive hazard elimination and full-process operational review. Hazard control requires continuous temperature monitoring of battery packs to prevent re-ignition, detection of combustible gas concentrations to ensure safety, and specialized cleanup operations at photovoltaic energy storage sites. The operational review should integrate data from automated warning systems with manual response records to analyze the causes of semi-automatic system failures and evaluate the timeliness of each response phase. These practical insights should then inform revisions to emergency response plans, improve the closed-loop management mechanism covering assessment, early warning, response, and review, and promote continuous iterative upgrades to the entire fire safety system.

4.4 System Coordination Framework

Effective system coordination requires establishing interconnected mechanisms that span the entire incident management cycle, including the phases before, during, and after incidents, to achieve deep integration of technical systems, management processes, and multi-stakeholder collaboration. In the pre-incident phase, data flow between risk assessment and monitoring systems must be seamless. Differentiated risk classification results should inform the configuration of multi-source perception systems, enabling targeted adjustments to sensor placement and alert thresholds to ensure monitoring priorities align with high-risk areas. Simultaneously, mechanisms linking hazard identification with equipment deployment should be established, pre-positioning adaptive resources such as automated fire blankets and specialized suppression equipment based on identified risk profiles.

Technically, intelligent coordination between monitoring and response systems is essential. Early warnings triggered by monitoring data should automatically activate corresponding suppression equipment. Unmanned stations require remote control platforms to enable seamless transition from detection to equipment activation. Managerially, automated equipment maintenance must be integrated into routine safety inspections, with operational protocols standardized according to training requirements to ensure constant readiness. For cross-entity collaboration, station safety systems should interface with fire rescue platforms, while integrated energy stations must enable safety data sharing among charging, storage, and other subsystems. Post-incident reviews should feed conclusions back into risk assessment and equipment configuration, forming a closed-loop coordination system of assessment, monitoring, response, and review to enhance overall prevention effectiveness.

The economic impact of the full-process fire safety framework is characterized by moderate short-term investment and substantial long-term net benefits. The initial investment (CNY 100,000–600,000 per station) can be fully recovered within three years through the avoidance of accident losses, improved operational efficiency, and policy subsidies. Furthermore, tailored cost-control solutions are available for various scenarios, including residential areas, highways, and coastal regions.

5 Conclusion

This study conducts a systematic investigation into the whole-process fire safety of charging stations, defining fire safety risks as a comprehensive representation of both the likelihood and severity of incidents resulting from multiple factors throughout the operational lifecycle. These risks exhibit distinct characteristics across different station types, such as unmanned stations, PV-integrated storage stations, and comprehensive energy stations. The analysis reveals significant shortcomings in existing fire safety systems, particularly in pre-incident assessment and early warning, during-incident response, post-incident review and optimization, and cross-phase coordination. To address these limitations, the proposed integrated framework incorporates targeted risk assessment and multi-source monitoring for pre-incident prevention, semi-automated equipment clusters and multi-dimensional coordination for during-incident response, and precise control mechanisms with lesson-based feedback for post-incident improvement. Supported by full-chain technical, managerial, and multi-stakeholder coordination mechanisms, the system establishes a closed-loop safety logic encompassing assessment, monitoring, response, and review. By integrating scenario adaptability, whole-process coverage, and collaborative closure, this framework provides scientific guidance for charging station fire safety practices and supports the secure development of new energy infrastructure.

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