ENVIRONMENTAL IMPACT ASSESSMENT OF SMOKE AND GAS DISPERSION FROM LITHIUM-ION BATTERY ENERGY STORAGE SYSTEM FIRES

Yi-Hao Huang[1]*

[1]Department of Fire Science, Wu Feng University, 117 Jianguo Rd., Sec. 2, Minsyong, Chiayi 62153, ROC.

*Corresponding Author: yihao.huang@wfu.edu.tw[1]

Abstract—The rapid expansion of lithium-ion battery energy storage systems (ESS) has raised increasing concern over their environmental and public health implications during fire events. ESS fires are characterized by prolonged combustion, frequent reignition, and the release of dense smoke containing hazardous gases such as hydrogen, carbon monoxide, methane, and toxic particulates. This study combines large-scale combustion experiments and computational simulations to examine the environmental dispersion of fire-induced emissions. A 10-foot ESS cabinet experiment recorded critical parameters including maximum smoke outflow velocity (33.93 m/s) and peak temperature (898 °C). Computational Fluid Dynamics (CFD) modeling using Fire Dynamics Simulator (FDS) and DNV Phast was employed to simulate smoke dispersion patterns, thermal radiation, and hydrogen release scenarios. Results revealed that uncontrolled ESS fires could generate flammable gas clouds exceeding 54 m in downwind LFL dispersion, while toxic smoke significantly impaired air quality across urban environments. Fireball and jet fire radiation extended up to 90 m and 64 m, respectively, with overpressure hazards reaching more than 300 m. These findings underscore the severe environmental burden posed by ESS fires, particularly in densely populated regions. The outcomes provide a scientific foundation for environmental risk management, regulatory safety distances, and community protection strategies in the deployment of large-scale ESS facilities.

Keywords— Environmental impact, energy storage systems (ESS), lithium-ion battery fire, smoke dispersion, toxic gas, CFD modeling..

I. INTRODUCTION

With the ongoing transformation of global energy infrastructure, energy storage technologies—particularly electrochemical energy storage systems—have become indispensable components of contemporary energy networks. The widespread adoption of energy storage facilities has significantly improved energy utilization efficiency, playing pivotal roles in balancing supply and demand, enhancing the integration of renewable energy sources, and stabilizing power grids. However, the rapid proliferation of these systems has concurrently raised substantial concerns among both the public and academia regarding their associated safety risks, particularly fire hazards.

Energy storage systems (ESS), especially those employing lithium-ion batteries, have gained widespread use due to their high energy density and superior charge-discharge efficiencies. Nevertheless, these batteries possess inherent risks related to thermal runaway [1], which can escalate swiftly into severe fires. Fires in energy storage facilities not only pose risks from thermal radiation and potential explosions [2] but also generate considerable quantities of toxic smoke, severely threatening environmental safety and public health [3], [4].

The generation of dense smoke is closely tied to the specific characteristics of ESS fires. During combustion, chemical decomposition and incomplete combustion processes release various hazardous gases and particulate matter, potentially including, but not limited to, carbon black, hydrogen fluoride, phosphoric acid, and numerous heavy metals [5]. The long-term environmental impacts of these pollutants necessitate further investigation.

Moreover, from environmental science and public health perspectives, smoke from ESS fires significantly affects air quality, warranting heightened attention. As urbanization continues to intensify, the deployment of energy storage systems in densely populated areas has become increasingly common. Consequently, the health implications for surrounding residents during fire incidents can be substantial. Existing research demonstrates that smoke emissions from ESS fires rapidly degrade air quality indices in adjacent areas, adversely impacting respiratory health among local populations.

Energy storage systems also present additional safety challenges beyond fire, including hazards associated with hydrogen leakage. Hydrogen is a highly flammable gas, and uncontrolled releases from ESS enclosures pose serious safety risks. Therefore, comprehensive analysis of hydrogen gas dispersion patterns following leakage incidents, and assessment of their environmental impacts, are critical.

This paper develops numerical models and conducts simulation studies to thoroughly examine hydrogen dispersion behaviors resulting from leakage events in ESS cabinets. These findings aim to provide scientific foundations for formulating effective emergency response strategies and safety protection measures. Ultimately, this research intends to draw increased attention from various stakeholders, encouraging further advancements in ESS safety technologies.

II. DESCRIPTION OF FIRE INCIDENTS

Incidents involving lithium-ion batteries, particularly within Energy Storage Systems (ESS), frequently exhibit hazardous characteristics that complicate mitigation efforts. Observations, notably from scenarios in Taiwan, highlight concerns including rapid fire propagation, the substantial release of both toxic and flammable gases, and complex challenges in fire suppression. Central to these events is the phenomenon of thermal runaway within the battery cells.

Thermal runaway is an uncontrollable, accelerating exothermic reaction within a cell, often triggered by factors, such as overcharging/discharging, excessive ambient temperatures, mechanical damage, or internal short circuits. This process results in a rapid temperature escalation and the ejection of cell components. Critically, thermal runaway liberates a mixture of gases, posing significant fire, explosion, and toxicity hazards.

Analysis indicates the release of flammable gases including hydrogen (H_2), carbon monoxide (CO), and total hydrocarbons (THC). The presence of these gases, potentially alongside oxygen released from cathode materials, create conditions conducive to ignition and sustained fire. Hydrogen is of particular concern due to its wide flammability range and extremely low Minimum Ignition Energy (MIE), cited as 0.019 MJ, rendering it easily ignitable.

In confined environments typical of ESS installations (e.g., containers), the accumulation of flammable gases resulting from incomplete combustion in oxygen-limited conditions presents a severe explosion risk. Subsequent introduction of air, for instance, upon opening access doors, can lead to the mixture entering its flammable range, potentially resulting in deflagration or flashover phenomena if an ignition source exists.

A. Vistra Energy Lithium Battery Plant Fire, Moss Landing, Monterey County, Northern California

On January 16, 2025, a significant fire erupted at the Vistra Energy lithium-ion battery facility located in Moss Landing, Monterey County, Northern California, persisting until January 18 before being fully extinguished. The facility, featuring a total battery storage capacity of 750 MW, generated extensive flames and substantial smoke emissions. The incident prompted the evacuation of approximately 2,000 residents and temporarily closed a nearby highway due to safety concerns, show in Fig. 1 [6].

B. Gateway Energy Lithium Battery Plant Fire, Otay Mesa District, San Diego

On May 15, 2024, the Gateway Energy storage facility in the Otay Mesa district of San Diego experienced a severe fire initiated by thermal runaway within lithium-ion battery storage units. The fire continued for 11 days and required continuous efforts from over 40 firefighters and five fire engines. Ultimately, the blaze was not extinguished by traditional firefighting methods but was allowed to burn out after consuming all available fuel. The Gateway storage station, operational since August 19, 2020, has a capacity of 250 MW and covers an area of approximately 80,000 square feet. The inherent complexity and chemical properties of lithium-ion batteries resulted in persistent re-ignition, complicating conventional fire suppression efforts. Additionally, combustion of lithium batteries releases toxic chemical gases, potentially causing a domino effect of escalating hazards, show in Fig. 2 [7].

Fig. 2 Fire incident at the Gateway lithium-ion battery energy storage facility, USA

C. Taiwan Energy Storage Cabinet Transport Fire Incident

On January 6, 2025, a truck transporting solar energy storage cabinets overturned in Taiwan, damaging internal battery components and creating an explosion hazard. As a precaution, surrounding roads, including a section of National Highway No. 1, were temporarily closed. Emergency responders remained on high alert as the storage cabinet contained over 3,000 lithium iron phosphate ($LiFePO_4$) batteries, which ignited following the vehicle overturn. The combustion persisted for approximately 4 to 10 hours. Environmental protection authorities monitored the scene due to significant visible black smoke and concerns about air pollution. Photographs documenting emergency response activities are presented in Fig. 3 [8]. Lithium battery fire incidents in Taiwan from 2022 to 2024 are summarized in Table 1.

Fig. 3 Fire incident involving overturned energy storage cabinet transportation on Taiwan National Highway

TABLE 1
Recent Lithium-ion battery fire incidents in Taiwan (2022–2024)

Date	**Location**	**Incident Description**
2022/3/18	Dawulun Industrial Zone,	Lithium-ion battery fire caused by AC380V charging/discharging equipment at a Seg Energy battery packaging plant.

2022/3/30	Keelung Longgang Road, Longjing, Taichung	Fire at an energy storage station using domestically produced NCM18650 cylindrical lithium-ion batteries, managed by ITRI. No casualties were reported.
2023/7/5	Near Longgang Road, Taichung	Fire at container storage facility with lithium iron phosphate batteries. Firefighters cooled batteries with water and extinguished fire with foam; no casualties reported.
2023/8/1	PChome warehouse, New Taipei	Fire lasting approximately two hours affecting four warehouses. Incident caused by thermal runaway of retired Gogoro scooter lithium batteries stored with tissue paper, leading to significant damage.
2022/10/23	Danshui Bus Depot, New Taipei	Two electric buses destroyed by fire, initially triggered by thermal runaway in lithium-ion battery during charging, spreading to adjacent bus. No casualties reported.
2024/1/22	Jinshan Road, Sanmin, Kaohsiung	Fire in a lithium battery factory warehouse containing numerous batteries and chargers. Quickly controlled by 116 firefighters; no casualties reported.
2024/2/21	Zhonghua Daxiong Ltd., New Taipei	Warehouse storing approximately 7,000 lithium batteries for Bluetooth earphones caught fire, spreading rapidly through cardboard boxes and debris from basement to third floor, producing toxic gases.

III. EXPERIMENTAL AND COMPUTATIONAL SIMULATION ANALYSIS

To enhance fire safety policies addressing energy storage system (ESS) incidents in Taiwan, accurate characterization of hazardous gas dispersion, particularly hydrogen released during thermal runaway events, is essential. Such precise dispersion data are critical for establishing scientifically-based safety perimeters, informing firefighter operational strategies—including approach paths, positioning, and appropriate personal protective equipment (PPE)—to minimize explosion and toxic exposure risks. Furthermore, this information significantly enhances emergency response protocols related to ventilation control, fire suppression techniques, and evacuation planning. Consequently, conducting targeted evaluations of hydrogen dispersion dynamics following ESS failures is vital for formulating robust safety guidelines and effectively mitigating severe incident outcomes within the Taiwanese context.

This study conducted a combustion experiment using a 10-foot energy storage cabinet, where thermal runaway was initiated by heating battery modules with heating pads, subsequently propagating to adjacent modules and packs. The battery utilized was a cylindrical-type 18650 cell with a layered lithium metal oxide cathode (denoted as CB, $LiNi_xMn_yCo_zO_2$, with x + y + z = 1), arranged in a 10S3P configuration (LG, 309.5 Wh), with a nominal voltage of 4.2 V. Each module consisted of 48 cells, and 12 modules were assembled into a single battery pack, totaling 12 packs for the experiment. Measurements recorded by the anemometer placed above the enclosure opening indicated a maximum airflow velocity of 33.93 m/s, and the highest temperature measured reached 898 °C. The combustion experiment setup is illustrated in Fig. 4.

Fig. 4 Combustion experiment of a 10-foot energy storage cabinet

A. Fire, Evacuation, and Dispersion Simulation

This study employed the Fire Dynamics Simulator (FDS) and Pathfinder software to simulate fire scenarios and evacuation processes. Developed by the National Institute of Standards and Technology (NIST) [9], FDS is a computational fluid dynamics (CFD) software utilizing field models to simulate diverse fire scenarios [10]. This software is internationally recognized and widely utilized [11]–[13]. The numerical model for the computer simulation in this study was constructed using FDS version 6.10.1. Experimental data from various sources, including relevant NIST studies, were integrated as input parameters for the FDS simulation.

Pathfinder software allows for the individual specification of pedestrian movement paths or the use of shortest evacuation routes, significantly aiding analysis of evacuation planning and pedestrian flow dynamics. Its high degree of flexibility in defining occupant behavior greatly facilitates evacuation scenario modeling in this study.

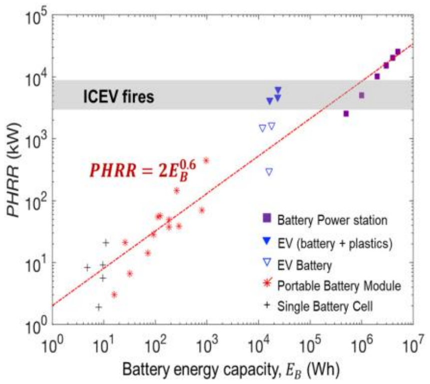
For large-scale dispersion assessment, the Phast software developed by DNV (Norway) was used. Phast, a Urban Dispersion Model (UDM) [14], was initially developed to meet the needs of the UK Ministry of Defence for predicting pollutant dispersion in urban environments. It has undergone extensive validation processes involving comparisons of model predictions against comprehensive measurements from field experiment databases. Phast effectively evaluates hazards associated with a range of flammable and toxic gases.

Given the extensive spatial domain of the fire simulation scenario, grid resolution significantly affects the accuracy of FDS simulations. Excessively large grid dimensions can reduce simulation accuracy, whereas overly small grids can exceed computational memory capacity, rendering simulation infeasible. Hence, an optimal grid size was calculated using Equation (1) [15]:

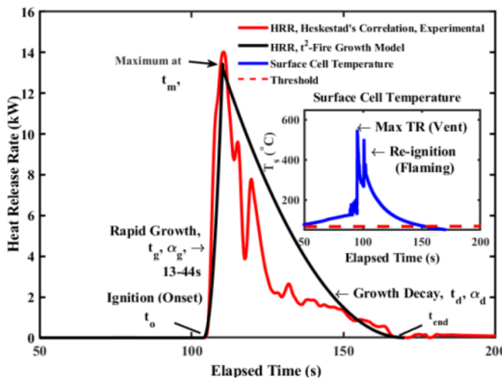
$$D^* = \left(\frac{\dot{Q}}{\rho_\infty \cdot C_P \cdot T_\infty \cdot \sqrt{g}}\right)^{\frac{2}{5}} = \left(\frac{q \cdot A}{\rho_0 \cdot \frac{T_0}{T_\infty} \cdot C_P \cdot T_\infty \cdot \sqrt{g}}\right)^{\frac{2}{5}} = \left(\frac{q \cdot A}{\rho_0 \cdot T_0 \cdot C_P \cdot \sqrt{g}}\right)^{\frac{2}{5}} \quad (1)$$

Where q denotes the heat release rate per unit area (HRR).

The simulated energy storage cabinet in this study had a capacity of 1.4 MWh (EB). The highest HRR, representing the worst-case scenario of full combustion, was estimated based on findings by Peiyi Sun [16], who provided HRR estimations for ternary lithium batteries. As depicted in Fig. 5(a), the HRR per storage cabinet was calculated as HRR = 2 × EB^0.6 kW = 9,743 kW. Due to the independent design of the battery cabinets and the implementation of fire-retardant containment structures designed to suppress fire spread, half of the calculated HRR value for ternary lithium batteries was adopted, yielding a peak HRR of 4,871 kW. Therefore, the peak HRR for this scenario was rounded to 5 MW. Additionally, referencing the fire growth model (t^2-fire model) from experimental results by R. E. Padilla [17], simulations were conducted using an HRR of 14 kW at 36 seconds, as illustrated in Fig. 5(b).



(a)Battery capacity and heat release rate prediction [16]



(b) Heat release rate measurements with the t2-fire growth model [17]

Fig. 5 Fire source design parameters

This study evaluated fire, smoke dispersion, and evacuation in a facility comprising 135 large energy storage cabinets, as illustrated in Fig. 6. The scenario involved a fire occurring in a single energy storage cabinet, assessing whether personnel within an adjacent building could safely evacuate. Pathfinder software was used to simulate evacuation scenarios involving 20 individuals inside the building. The nearest energy storage cabinet to the building was located 12 meters away, and 16 meters from the building exit, with a 5 m/s wind directed from the cabinet towards the building to simulate adverse conditions. Simulation results indicated that the smoke and thermal radiation from the cabinet did not impede evacuation paths due to the distance exceeding 10 meters, as shown in Fig. 7.

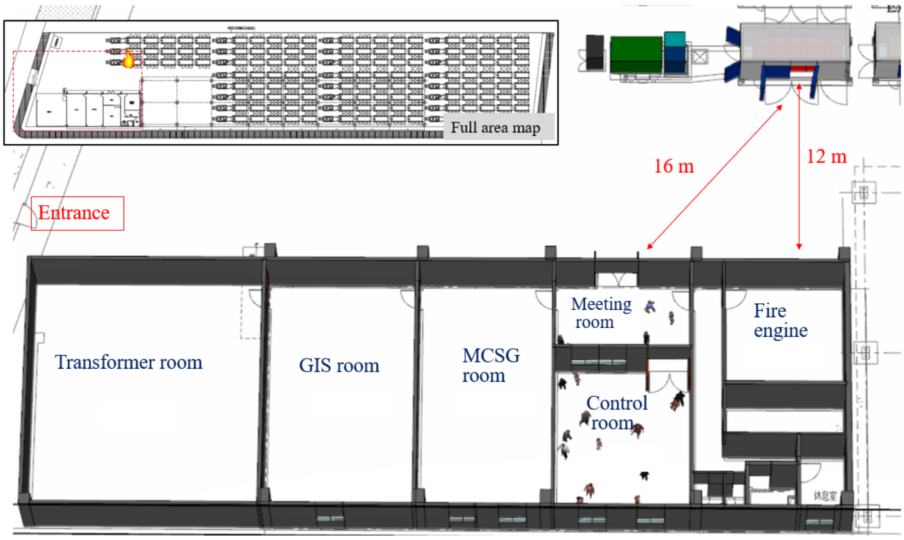


Fig. 6 Simulation overview and fire ignition location

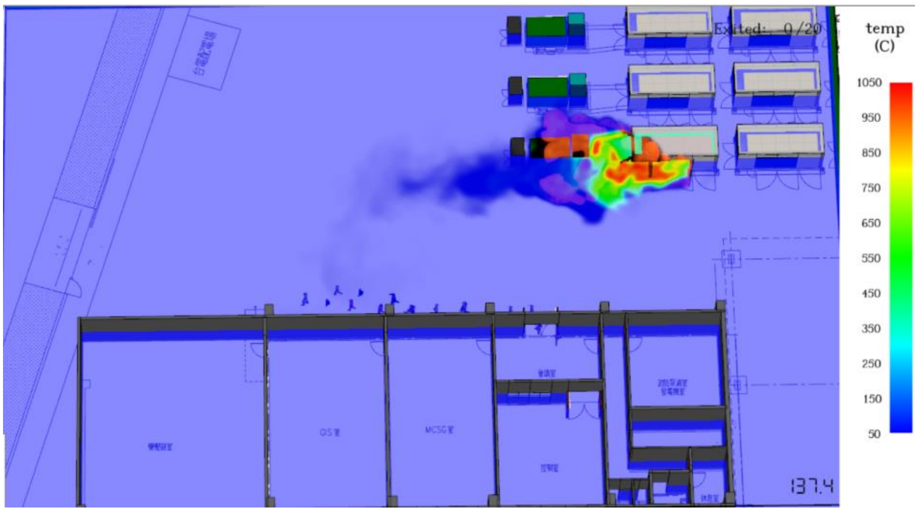


Fig. 7 Smoke from energy storage cabinet does not

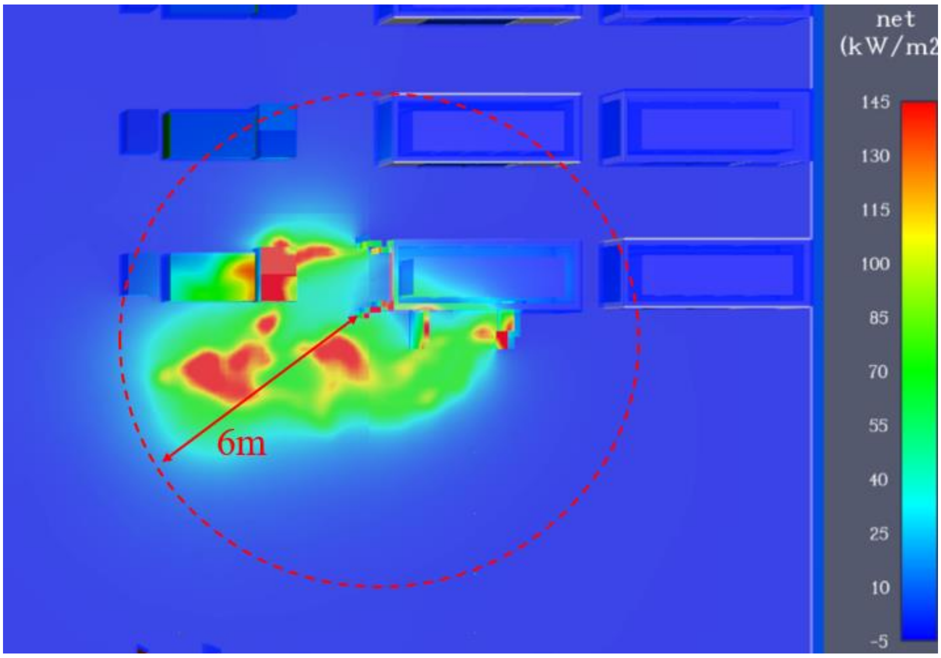


Fig. 8 Thermal radiation impact range

B. Large-Scale Smoke Dispersion Impact Asessment

Thermal runaway describes an uncontrollable and rapidly accelerating exothermic reaction within battery cells, typically initiated by factors such as overcharging or discharging, elevated ambient temperatures, mechanical damage, or internal short circuits. This phenomenon results in rapid temperature elevation and subsequent expulsion of cell contents. Crucially, thermal runaway generates a complex mixture of gases, significantly increasing risks related to fires, explosions, and toxic exposure.

Smoke dispersion was simulated using Phast software under the scenario of an energy storage cabinet fire with an open door, resulting in smoke release (referencing Fig. 4). The leakage area was set at 1.579 m², with the cabinet containing 396,480 batteries, each rated at 5 Ah, totaling 1,982,400 Ah. Based on literature, gas production was estimated at 1.96 L/Ah [18], resulting in a simulated total gas volume of 3,885,504 L. The gas composition was H_2: 42.8%, CO: 37.1%, CO_2: 10.0%, CH_4: 3.0% [19]–[21], with leakage duration set at 4 hours. Environmental conditions were summer-specific, with a temperature of 28.5°C, humidity of 84.0%, wind speed of 1.88 m/s, atmospheric stability class A, and southward wind direction [22].

The summer scenario displayed the greatest dispersion due to favorable conditions for longer-range gas transport, including weaker vertical mixing. Dispersion modeling revealed that the farthest Lower Flammability Limit (LFL, 2.7%) dispersion distance reached 54.22 m at a height of 23.96 m, as shown in Fig. 9. Fireball radiation reached distances of 89.35 m, 50.33 m, and 26.85 m for intensity levels of 4, 12.5, and 37.5 kW/m², respectively (Fig. 10). Jet fire distances for corresponding intensities were 63.99 m, 52.32 m, and 45.31 m (Fig. 11). Overpressure impacts reached distances of 302.38 m, 58.77 m, and 44.06 m for intensities of 0.02068, 0.1379, and 0.2068 bar, respectively (Fig. 12).

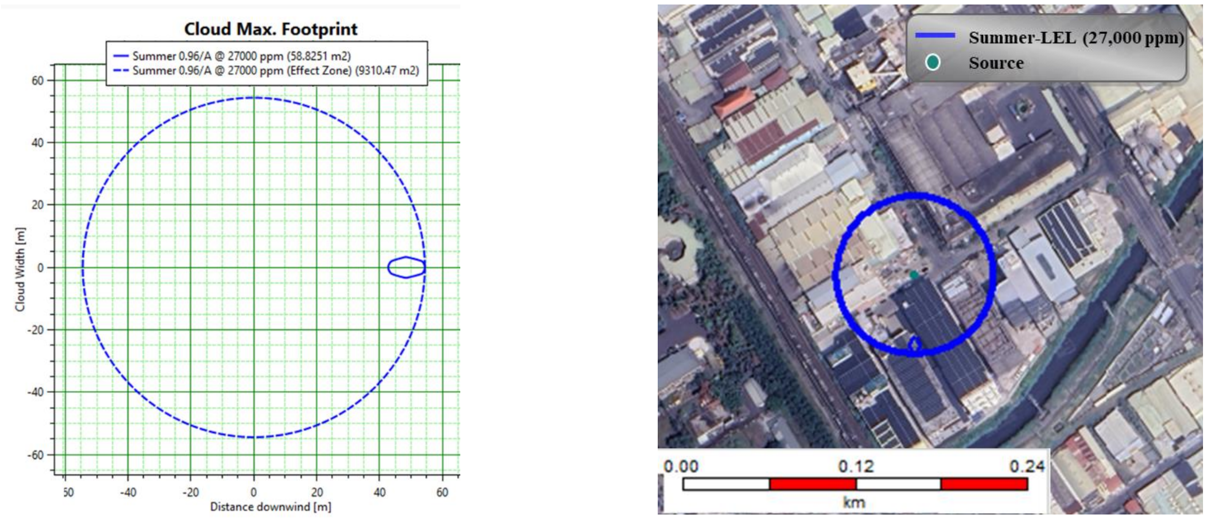


Fig. 9 Lower Explosive Limit (LEL) consequence and effect zones at the specified location (near city) based on Ethylene LEL values

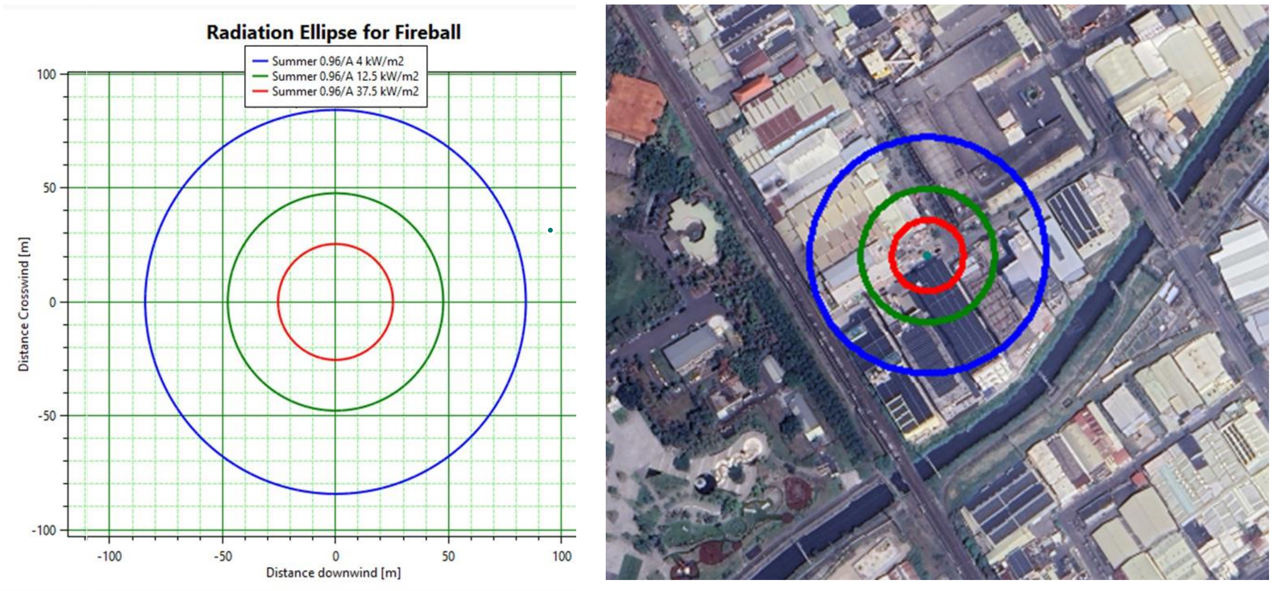


Fig. 10 Fireball consequence and effect zones at the specified location (near city)

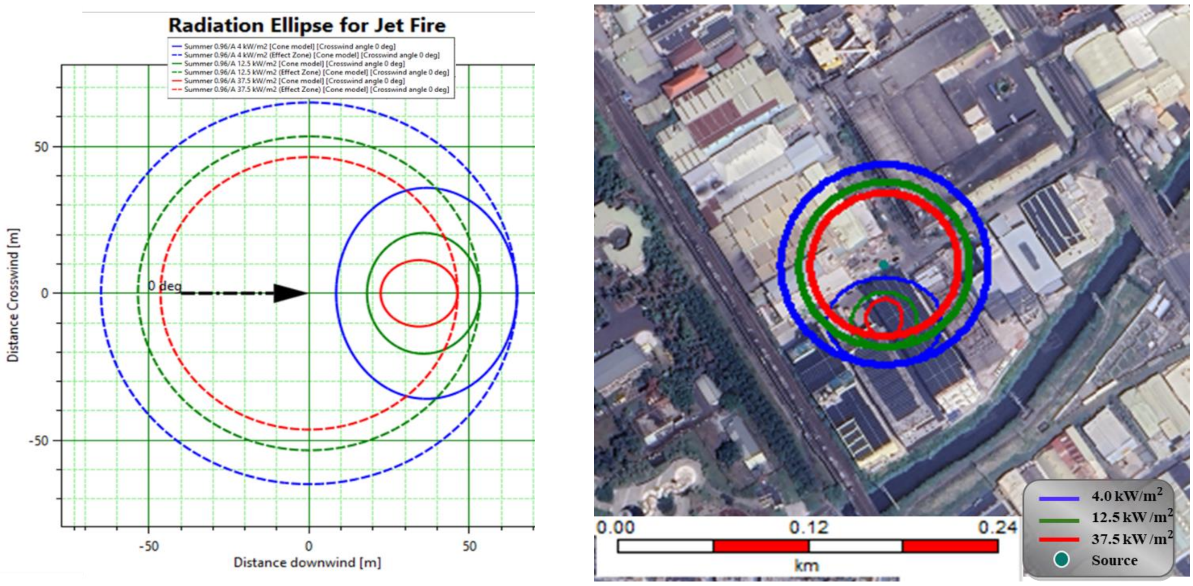


Fig. 11 Jet fire consequence and effect zones at the specified location (near city)

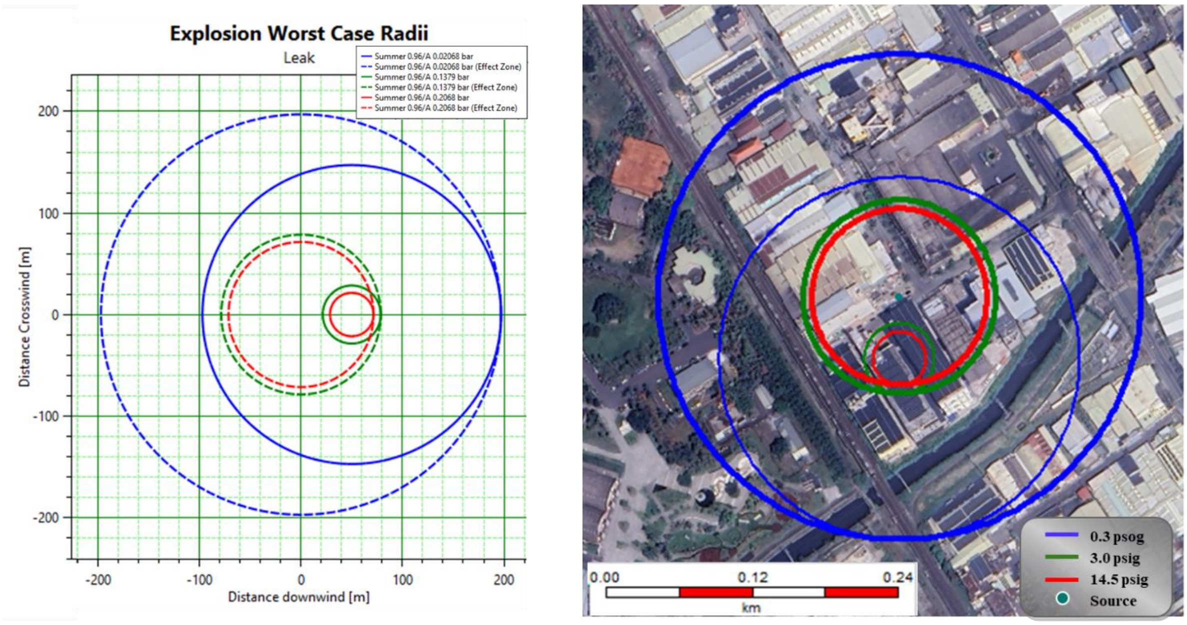


Fig. 12 Explosion consequence and effect zones at the specified location (near city)

IV. CONCLUSION

This study developed a computational model using Fire Dynamics Simulator (FDS) for an outdoor lithium iron battery energy storage system (ESS). The scenario involved a single energy storage cabinet undergoing combustion, assessing its impact on the surrounding environment and occupant evacuation conditions, thereby evaluating fire safety perimeters. Additionally, extensive smoke dispersion was simulated using DNV Phast software to analyze potential large-scale impacts. Results indicated that without protective measures, thermal radiation remained below 10 kW/m² within 1.2 meters horizontally and up to 3.5 meters vertically around the cabinet, typically ranging between 5 and 8.1 kW/m². The maximum temperature reached was approximately 580°C, with sustained temperatures between 305°C and 470°C. In open-field conditions, the downwind thermal radiation impact did not exceed 6 meters; however, the lack of proper venting could lead to physical explosion hazards due to gas expansion.

Simulations showed that if an ESS cabinet fire remains uncontrolled for four hours, smoke dispersion could reach a maximum Lower Flammability Limit (LFL, 2.7%) dispersion distance of 54.22 meters at an altitude of 23.96 meters. In case of an explosion, the fireball could impact distances up to 89.35 meters at an intensity of 4 kW/m^2, while jet fire impacts could reach 63.99 meters. Overpressure impacts at the lowest intensity level (0.02068 bar) could extend as far as 302.38 meters. These results suggest that if the ESS fire cannot be rapidly controlled, evacuation of residents in downwind alert zones may be necessary, and residents outside these zones should be advised to keep doors and windows closed and avoid outdoor activities until the emergency subsides.

To enhance fire safety policies for ESS incidents in Taiwan, accurately characterizing hazardous gas dispersion following thermal runaway, particularly hydrogen, is crucial. Such data informs evidence-based safety perimeter establishment, guides firefighter operational tactics (including approach strategies, positioning, and PPE selection) to minimize exposure risks, and optimizes overall emergency response procedures involving ventilation, fire suppression, and evacuation. Therefore, focused analysis of hydrogen dispersion dynamics post-ESS failures is vital for developing robust safety protocols and effectively mitigating severe outcomes associated with such incidents within the Taiwanese context.

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