EPRI

2024 White Paper

Lessons Learned from Air Plume Modeling of Battery Energy Storage System Failure Incidents

TABLE OF CONTENTS

Abstract 2

Introduction 2

Model Design Options................. 3

- Modeling Tools 3
- Model Characteristics 4
- Computational Fluid Dynamics Models vs. Chemical/ Dispersion Models 4

Model Input Selections 4

- Emission Rates......................... 5
- Wind Conditions 6

Human Health Criteria and Guidelines.................................... 6

Extent of Conservatism 8

Scenarios Considered.................. 9

Additional Insights 9

Knowledge Gaps 10

Appendix: EPRI's Emission Calculation for Recent BESS Fire Plume Modeling Scenarios.........11

ABSTRACT

An improved understanding of the potential downwind impacts of a failure incident—such as thermal runaway-induced off-gassing or fire at a battery energy storage system (BESS) with subsequent gas and particle release to the atmosphere—enhances the ability to determine appropriate response to battery fires.

One approach to exploring the range of potential outcomes is air plume simulation modeling, which incorporates emissions, atmospheric dispersion, and transformation (for example, chemical reactions or physical changes such as deposition) of the chemicals present within a plume. This document provides an overview of various plume modeling tools that are available for such simulations, key model characteristics needed, important input metrics, guidelines for scenario building, and current knowledge gaps in the field. The goal is to educate BESS owners and operators, industry professionals, the emergency response community, and researchers as to current practices, drivers of plume evolution, information gaps, and future research needs.

INTRODUCTION

Battery energy storage system (BESS) failures have the possibility of evolving into thermal runaway, with associated cell rupture and off-gassing. This has the subsequent possibility of a fire ignition with a resulting combustion plume. Whether or not there is a flame, BESS failures emit gases and particles to the atmosphere, which can move downwind and potentially evolve through chemical reaction or physical processes (e.g., deposition to ground or other surfaces) as they are transported. This evolution may also be referred to as "fate and transport." Owners and operators must implement safety mitigation technologies and operational approaches to reduce risks of failures, as well as perform hazard assessment and community risk assessment evaluations to understand the range of potential on-site or downwind impacts. This includes simulation modeling of air plume evolution.[1,2]

While currently not required in most jurisdictions, reporting information on the potential toxic emissions from BESS fires and air modeling simulation results was suggested for inclusion in the next update of the National Fire Protection Agency 855 *Standard for the Installation of Stationary Energy Storage Systems* (current version 2023 Edition[3]) through the NFPA 855 Task Group 6 review of HF and other toxics production. Another suggestion to this working group was to recommend performing a plume dispersion study if there are occupied buildings with ¼ mile of a BESS >600 kWh. Neither was selected for final inclusion into the current 2023 version due to outstanding uncertainties, although this guideline is

1 *Air Modeling Simulations of Battery Energy Storage System Fires*. EPRI, Palo Alto, CA: 2022. 3002021777.

2 *Near-Field Air Modeling Tools for Potential Hazardous Material Releases from Battery Energy Storage System Fires*. EPRI, Palo Alto, CA: 2020. 3002020094.

3 National Fire Protection Agency 855 Standard for the Installation of Stationary Energy Storage Systems, 2023. https://www.nfpa.org/codes-and-standards/8/5/5/nfpa-855.

recommended for use when possible by an electric power company.[4] Additionally, community impacts of potential BESS failures are increasingly becoming a focus of both public concern and the facility permitting process. Plume modeling can address these concerns by contributing to knowledge on:

- Potential site consequences and first responder exposures,
- Potential consequences at offsite locations,
- Site-specific emergency response planning (ERP), including personal protective equipment (PPE) recommendations and staging area locations,
- Range of efficacy of protective actions (e.g., shelter-in-place or evacuation),
- Environmental impacts,
- Possible setback distances,
- Facility planning and site selection processes, and
- Success of various BESS design and mitigation actions taken.

Off-gassing or combustion plume modeling allows for testing of potential impacts from a wide range of BESS designs, meteorology, locations, topography, nearby building structure, fire dynamics, suppression techniques and management approaches. The model results can also be used to determine the individual factors that most heavily influence the final ambient concentrations and exposures.

As part of the Battery Energy Storage Fire Prevention and Mitigation Phase 2 Supplemental Project,[5] a series of site-specific air quality modeling studies for simulated BESS fires have been performed. The goal was to improve understanding of the resulting potential spatial and temporal exposure, understand primary drivers of exposure, and provide feedback to the BESS facility design process.

This report summarizes the lessons learned from these modeling efforts of both the pre-combustion off-gassing (thermal runaway) and combustion phases of a BESS failure and provides suggestions that can be applied to future modeling efforts, regarding of the models or BESS designs used.

MODEL DESIGN OPTIONS

Modeling Tools

A variety of acceptable modeling tools are available that can be modified to address the needs of modeling BESS off-gassing and fire plumes, including Appendix W[6] tools. These include:

- AERMOD (*A*merican Meteorological Society and U.S. *E*nvironmental Protection Agency *R*egulatory *Mod*el) - a steady state Gaussian[7] plume model maintained by the U.S. EPA and commonly used for facility permit modeling. AERMOD does not account for dense gas effects that can occur during electrolyte off-gassing or at lower states of charge.
- FDS (Fire Dynamics Simulator) - a computational fluid dynamics (CFD) model developed by the National Institute of Standards and Technology. The code solves the Navier-Stokes equations describing conservation of mass using large-eddy-simulation approach for turbulence and is widely used for low-speed flows and smoke and heat transport from fires. The code has been extensively validated for a variety of scenarios involving fire, smoke, and gas dispersion. The tool is intended for detailed modeling of fire and gas plumes in outdoor conditions.
- PHAST – Process Hazard Analysis Software is a proprietary commercial model that can be used to analyze accidental releases from their starting point to distant areas.
- SAFER/TRACE - TRACE was developed to evaluate impacts of toxic chemical spills. This model is a proprietary version of TRACE developed and maintained by Systematic Approach for Emergency Response (SAFER). It incorporates over 600 different compounds in its chemical library.

4 Mylenbusch, I.S., Claffey, K.J., and Chu, B.N (2023) Hazards of lithium-ion battery energy storage systems (BESS), mitigation strategies, minimum requirements, and best practices. Process Safety Progress, 42(4), 664-673. https://doi.org/10.1002/prs.12491.

5 *Battery Energy Storage Fire Prevention and Mitigation Phase II Supplemental Project Notice*. EPRI, Palo Alto, CA: 2021. 3002022509.

6 Appendix W is the U.S. EPA Guideline on Air Quality Models that provides recommended models and techniques for modeling of ambient concentrations of air pollutants. https://www.epa.gov/scram/2017-appendix-w-final-rule.

7 A Gaussian model is probabilistic and describes a three-dimensional concentration field generated by a point source under stationary meteorological and emission conditions.

- SCICHEM – a Lagrangian[8] model used for the simulation of atmospheric dispersion using puffs. It is the basis for the US federal government Hazard Prediction and Assessment Capability Joint Effects Model (HPAC/JEM) emergency release models. This tool allows for the potential atmospheric chemistry of emitted pollutants to be included, avoids artificial diffusion problems in Eulerian models, and accurately treats length scales as plumes evolve.

More information on the pros and cons of these tools can be found in an EPRI report.[9]

Model Characteristics

Characteristics of the potential atmospheric models should be considered before use with BESS fire plumes. Key characteristics are listed below. While not all desired scenarios may require all the below features, if a tool is missing a substantial number of these it may be inappropriate for modeling of BESS off-gassing or fire plumes. When the user has a sense of the scenarios of interest for evaluation, review of the below characteristics can help confirm an appropriate modeling tool choice.

Desired Variables

- Meteorology:
  - Wind speed and direction
  - Temperature
  - Humidity
  - Rainfall rates
  - Stability or turbulence profiles
- Chemical:
  - Chemical characteristics (e.g., concentration, density, thermodynamic properties)
  - Explosion parameters (e.g., estimates of heat release rate and total released heat)

Desired Capabilities

- Models gaseous and particulate matter (PM) plumes (e.g., combustion) and dense gas plumes (e.g., off-gassing plume)
- Models buoyant plumes (e.g., combustion or otherwise heated plume)
- Models explosions
- Models industrial applications
- Incorporates complex terrain, including nearly building structures
- Incorporates changes in meteorology parameters
- Outputs averaging times in seconds/minutes
- Fast setup and run time
- Reduced complexity

Computational Fluid Dynamics Models vs. Chemical/Dispersion Models

The SCICHEM model that EPRI has selected for use with BESS off-gassing and fire scenarios incorporates chemical transformation plus dispersion (i.e., movement throughout atmosphere), provides for high spatial and temporal resolution modeling, and allows simulations that extend multiple kilometers from the site to capture nearby community exposure. Additionally, SCICHEM can be used with the Building Profile Input Program for PRIME preprocessor to understand how the downwash caused by surrounding buildings may affect plume dispersion. CFD tools like FDS are useful to represent near field impacts from the horizontal flow around nearby buildings and structures, but their computational expense means the CFD modeling domain usually cannot be extended more than a fraction of a kilometer downwind.

MODEL INPUT SELECTIONS

This section discusses typical metrics used during the modeling of off-gassing or fire plumes. Ideally, information specific to the project and location of interest would be used for all input metrics. However, since the science of BESS failure management and plume modeling is a new field, not all information may be explicitly available. Assumptions based on engineering or scientific judgement will likely be required. Additionally, some modeling tools may have default values that can be used after evaluation and confirmation of relevance to the scenario of interest. The rapid evolution of this field suggests frequent review of the state-of-the-science in upcoming years will identify an increasing number of sources for documented input values.

It is important to document all assumptions on input values and other scenario characteristics to clearly communicate the level of uncertainty and conservatism of the results,

8 Lagrangian models follow air parcels as they move with the wind, allowing for calculation of transformations at each model time step.

9 *Air Modeling Simulations of Battery Energy Storage System Fires.* EPRI, Palo Alto, CA: 2022. 3002021777.

and to retain the ability to compare against other modeling efforts. Key information needs on BESS design and site locations that impact final concentration estimates include the following:

1. Total battery weight (kg) and storage capacity (kWh) for estimating heat release and pollutant emissions,
2. BESS dimensions for initial source size inputs,
3. Number of modules to which thermal runaway might propagate (aka propagation cycles) during an event,[10]
4. Presence/location of ventilation ports (e.g., vent piping, deflagration panels), understanding of ventilation type (e.g., active/passive, deflagration-based)
5. Heights and dimensions of all nearby structures that can block the winds as well as major topography (e.g., located in a valley), and landscape type (e.g., forested, agricultural)
6. Locations of nearest off-site human populations and sensitive groups,
7. Battery chemistry (*This is helpful, but as the range of emissions for batteries of similar chemistry are large and overlap with those from other chemistries, this may not be the driving factor in the results*), and
8. Battery state-of-charge (SOC) (*Higher SOC values are more likely to result in flaming combustion, which lofts and dilutes the combustion plume and subsequent reduces near-surface concentrations as compared to low SOC cases. Low SOC cases are more likely to result in dense off-gassing plumes of volatilized electrolyte that hug the ground surface, look like white fog, and increase estimated concentrations as compared to high SOC scenarios*).
9. Emission rates
10. Heat release rates and temperatures of off-gas or combustion plume
11. Minimum wind speed

10 One responsible approach is to assume 3 thermal runaway propagations in one hour (one every 20 minutes) with approximately 5 °C of temperature rise per minute. This can be considered a maximum credible event for large BESS. Venting can occur at 120 °C, so a 100 °C temp rise from ambient to 120 °C in 20 minutes is credible. The source term could be reduced to one module if UL 9540A tests justify it and if the test can be trusted.

Emission Rates

Due to their important driving effect on downwind exposures, emission rates during combustion and off-gassing are a key set of assumptions used in plume modeling. While results from a number of laboratory burn tests for lithium ion battery modules are publicly available[11,12,13,14] a knowledge gap currently exists as to the emission rates from real-world incidents, including chemical and physical dynamic evolution of the emitted pollutants close to the source. Fire service or hazardous materials team statements to the public on real-world incidents often state no presence of toxic gases. However, the chemicals tested, instruments/tools used, and the location and timing of measurement are rarely disclosed. It is known that easily accessible tools for measuring some chemicals of interest are susceptible to confounding by other chemicals. Determining accurate, precise, and field-deployable methods that can be engaged quickly in the event of a real-world fire are critical to improved understanding of human exposure risks. Use of UL 9540A test results as a total emitted chemical mass can be a good starting point for determining the magnitude of the source term. However, these results can be uncertain because real-world incidents have proven that more modules can be affected in a real-world incident that what was observed during 9540A testing in the laboratory. A conservative approach for the pre-combustion (or off-gassing) case would be to assume thermal propagation between modules occurs twice within 60 minutes to provide 3 modules off-gassing without ignition.[15] Additionally, emission rates differentiated by battery chemistry are not a substantial driver of results at this point because the existing laboratory data demonstrates wide ranges of emission rates for each chemistry that substantially overlap. Additional emissions

11 *Lithium ion Battery Thermal Runaway Propagation and Emissions Analysis*. EPRI, Palo Alto, CA: 2021. 3002021644.

12 *Summary of Prior Electrochemical Battery Fire Emission Characterization Studies*. EPRI, Palo Alto, CA: 2020. 3002018741.

13 Premnath, V., Wang, Y, Wright, N., Khalek, I., and Uribe S. 2022. Detailed characterization of particle emissions from battery fires. Aerosol Sci. Tech. 56 (4) 337-354. https://doi.org/10.1080/02786826.2021.2018399.

14 Quant, M., Willstrand, O., Mallin, T., and Hynynen, J. 2023. Ecotoxicity evaluation of fire-extinguishing water from large-scale battery and battery electric vehicle fire tests. Environ. Sci. Technol. 57 (12) 4821-4830. https://doi.org/10.1021/acs.est.2c08581.

15 For example, if the first 50 KWH module is in thermal runaway, assume that the second and third modules can go into TR without ignition within the first 60 mins, to yield a source term or battery size of 150 KWH.

data will need to be collected in the future to further clarify these effects.

Wind Conditions

The highest modeled concentrations in BESS off-gassing and fire scenarios occur during calm wind conditions; the concentrations become disproportionally higher as zero wind speed is approached. Based on EPRI wind speed sensitivity testing, assuming a minimum wind speed of at least 0.5 m/s substantially reduces these disproportionate concentrations and is more physically relevant given the difficulty of defining wind conditions representative of an hourly timestep if measurements are not available.

There are two regulatory approaches that can inform wind condition selection: the U.S. EPA Risk Management Program (RMP) under Section 112 (r) versus U.S. EPA National Ambient Air Quality Standard (NAAQS) approach, both under the Clean Air Act Amendments. RMP requires facilities that use extremely hazardous substances[16] to develop a Risk Management Plan, which must be revised and resubmitted to EPA every five years. The NAAQS set required limits on ambient concentrations for pollutants that are common in outdoor air, considered harmful to public health and the environment, and that come from numerous and diverse sources (i.e., CO, $PM_{2.5}$, PM_{10}, NO_2, Pb, O_3, and SO_2). The two approaches are compared below for their wind speed, atmospheric stability and effective plume rise guidance.

1. **Wind speed and stability:**
   - The NAAQS approach uses all meteorological data on speed and direction without edits, leading to high concentrations for cases with zero wind speed and stable atmosphere (Pasquill stability class F). This is very conservative.
   - The RMP approach uses only the prevailing wind direction, wind speed of 1.5 m/s, and stable atmosphere (Pasquill stability class F).[17] This is less conservative.
2. **Effective plume rise:**
   - The NAAQS approach uses vertical velocity and temperature at the source to calculate effective plume rise. This is negligible for thermal runaway and generally small for low heat release assumptions.
   - The RMP approach assumes effective release height of 30 ft and 150 ft, effectively assuming negligible heat release. For large fires, this may be overly conservative.

EPRI's modeling efforts to date have used minimum wind speeds of 1.5 m/s to simulate calm conditions, and included an RMP-style scenario in the event its lower plume rise leads to higher surface concentrations. Additionally, multiple years of actual nearby meteorological data are used to determine the most appropriate nearby surface and upper air winds over diurnal cycles.

HUMAN HEALTH CRITERIA AND GUIDELINES

A variety of health criteria options are available for comparison against modeled concentrations, but the most used are the Immediately Dangerous to Life and Health (IDLH)[18] and one or more levels of the Acute Exposure Guideline Level (AEGL).[19] Similar exposure times for different criteria may result in a range of different acceptable concentrations. Table 1 and an EPRI report[20] provide further information. The most relevant criteria to use depends on for whom the exposure may occur. First responders and on-site personnel exposures likely occur nearest to the source and should be compared to IDLH criteria. IDLH reflects a concentration limit for time frames beyond which would result in irreversible and long-lasting adverse health effects, death, or prevent escape from such an environment. Any exposures to the surrounding population would occur downwind after dilution and can be compared to U.S. EPA Acute Exposure Guideline Levels (AEGLs) or similar criteria. AEGL-1 values reflect the lowest concentration at which a member of

16 U.S. Environmental Protection Agency Risk Management Program Rule August 22, 2023. https://www.epa.gov/rmp/list-regulated-substances-under-risk-management-program-rmp-program.

17 The Code of Federal Regulations for Chemical Accident Prevention Provisions 40 CFR 68.229(b) states *"For the worst-case release analysis, 1.5 meters per second wind speed and F atmospheric stability class must be assumed, unless the stationary source owner or operator can demonstrate that local meteorological data applicable to the stationary source show a higher minimum wind speed or less stable atmosphere at all times during the previous three years."*

18 The National Institute for Occupational Safety and Health (NIOSH). Immediately Dangerous to Life or Health (IDLH) Values. May 10, 2019. https://www.cdc.gov/niosh/idlh/default.html.

19 U.S. Environmental Protection Agency Acute Exposure Guideline Levels for Airborne Chemicals. March 21, 2024. https://www.epa.gov/aegl.

20 *Approaches for Evaluating Potential Human Health Consequences of Utility-Scale Lithium ion Battery Failures*. EPRI, Palo Alto, CA: 2021. 3002021634.

the general population, including susceptible individuals, would experience discomfort and irritation. However, at the AEGL-1 concentration the effects are not disabling, are temporary, and are reversible upon cessation of exposure. At AEGL-2, the effects may be irreversible or disabling. One potential emitted chemical of concern is hydrogen fluoride (HF). HF permissible exposure limits range several-fold depending on the guideline and exposure timeline selected. Table 2 lists a few relevant values. All criteria selected, and the reasons why, should be documented.

Table 1. *Summary of Common Health-Protective Air Exposure Limits for Public and Worker Protection.*

Public Protection

ISSUING BODY	LIMIT OR GUIDELINE	USE	POPULATION COVERED	EXPOSURE PERIOD	NOTES/DETAILS
Environmental Protection Agency (EPA)	**Acute Exposure Guideline Level (AEGL)**	Rare exposure to airborne chemicals	General public, including sensitive individuals	10-min. 30-min, 60-min, 4-hour, 8-hr	AEGL-1: transient, non-disabling effects; AEGL-2: irreversible or disabling; AEGL-3: life-threatening
American Industrial Hygiene Association (AIHA)	**Emergency Response Planning Guidelines (ERPGs)**	Single exposure to airborne chemicals; use when AEGLs are not available	General public, excluding sensitive individuals	1-hr	ERPG-1: transient, non-disabling effects; ERPG-2: irreversible or disabling; ERPG-3: life-threatening

Worker Protection

ISSUING BODY	LIMIT OR GUIDELINE	NOTES/DETAILS
American Conference of Government Industrial Hygienists (ACGIH)	**Threshold Limit Values (TLVs)**	Time-Weighted Average (TWA) – time-weighted-average concentrations for 8-hr workday (40 hr/week). Allow repeated exposure with no adverse effects.
		Short-Term Exposure Limit (SATEL) – 15-min TWA concentrations for 8-hr workday (40 hr/week). Allow up to four exposures/day with no adverse effects if TLV-TWA not exceeded.
		Ceiling (C) - concentration not to be exceeded under any circumstances
National Institutes of Occupational Safety and Health (NIOSH)	**Recommended Exposure Limits (RELs)**	8-hr or 10-hr TWA or ceiling concentration
Occupational Safety and Health Administration (OSHA)	**Permissible Exposure Limits (PELs)**	Generally equivalent to ACGIH TLVs. Enforceable.

Table 2. *A Selection of Permissible Exposure Limits for HF. This does not cover the full range of values for all guidelines.*

HEALTH CRITERIA GUIDELINE	PERMISSIBLE LIMIT FOR HF (PPM)
Emergency Response Planning Guidelines (ERPG-2[21]) over 1 hour	20
Acute Exposure Guideline Levels (AEGL-2) over 1 hour	24
Immediately Dangerous to Life or Health (ILDH) over 30 minutes	30
Acute Exposure Guideline Levels (AEGL-2) over 10 minutes	95
Acute Exposure Guideline Levels (AEGL-1) over 1 hour	1
Acute Exposure Guideline Levels (AEGL-1) over 10 minutes	1

21 American Industrial Hygiene Association. Essential Guidelines for Emergency Response. August 23, 2022. https://www.aiha.org/blog/essential-guidelines-for-emergency-response.

EXTENT OF CONSERVATISM

A key area requiring clarification is the extent of conservatism that is most appropriate for the selection of input values (such as the emission rates) and scenario design in any given analysis. A range of options exist that may depend on the desire to understand certain conditions, a requirement based on a permitting or other regulatory authority, and research advances in BESS fire dynamics and modeling. While many are interested in the colloquially termed "worst case scenario," that is a nebulous term, especially when most necessary input values have wide possible ranges and unclear probability distributions across those ranges. More useful paradigms that can each be simulated for a given site may include "realistic and probable," "realistic and improbable," "conservative and probable," and "conservative and improbable." A "worst case scenario" would be expected to be more unlikely than "conservative and improbable."

Stacking multiple conservative assumptions, even if not "worst case," can result in unrealistically conservative results. One way to address this is to look at large range of meteorological conditions over a year and look at the statistical frequency or probability distribution of the results. Including tables of modeling results based on time of day and wind speed can be helpful to documenting the percentile frequency of results. A plume that would be an issue during 100% of the hours in a year if thermal runaway occurs is much more notable than if it would pose issues during only 1% of the hours.

Most researchers and practitioners in the field agree that conservative assumptions that would overestimate the impacts of a potential event should be used as part of the scenario building. However, there remain many knowledge gaps that influence those assumptions and the appropriate level of conservatism.[22] One prior risk analysis suggested that BESS failures could only occur once every 10 to 100 years;[23] another suggested 1% of all BESS containers on average could experience a failure in one of its battery cells.[24] Another approach using calculations of fire events divided by the number of operating years of facilities on the U.S. electrical grid estimated 1 event per 500+ facility years.[25] Safeguards such as battery management systems, redundant HVAC (Heating, Ventilation, and Cooling) units with failure alarms, and fire suppression systems can further reduce the odds of a battery module going into thermal runaway following failure; DNV GL estimate this several years ago as dropping to once in every 100,000 to 1,000,000 years (DNV GL, 2019). Current estimates based on the real-world amount of 67 GW and 150 GWh of lithium ion BESS deployed globally at the end of 2023,[26] and 85 failure incidents by that time,[27] results in 1 incident per 1.76 GWh deployed. This is an *order of magnitude less frequent* than 1% incident and 1 in 10 million 18650-type cell predictions. Thus, the odds of any gas release from the proposed battery container are already very low and continually getting lower. If thermal runaway occurs in a battery module, additional mitigations through the battery management system controls or thermal barriers between modules reduce the odds of the thermal runaway spreading to half of a rack of modules. If it does, it is still unlikely to release the upper limit emissions estimates. Additionally, not all thermal runaway events will lead to combustion,[28] and thus the odds of a fire are even lower than those of a thermal runaway. When combustion does occur, it is unlikely to occur with the maximum emission rates and is further unlikely to occur at the worst possible time (calm winds and a stable nighttime boundary layer). Thus, use of these types of scenarios and inputs are over-protective simulations that almost certainly would overestimate the actual impact of an extremely unlikely fire event at the stationary energy storage system.

22 *Approaches for Evaluating Potential Human Health Consequences of Utility-Scale Lithium ion Battery Failures*. EPRI, Palo Alto, CA: 2021. 3002021634.

23 DNV GL, 2019: Quantitative Risk Analysis for Battery Energy Storage Sites. DNV GL Energy Insights, Chalfont, PA.

24 National Fire Protection Association (NFPA). 2020. "Beyond EVs: Stranded energy is a concern across all energy storage technologies." https://www.nfpa.org/News-and-Research/Publications-and-media/NFPA-Journal/2020/January-February-2020/Features/EV-Stranded-Energy/ESS.

25 Jensen Hughes, 2023. Personal communication.

26 Energy Storage News. June 15, 2023. https://www.energy-storage.news/global-bess-deployments-to-exceed-400gw-annually-by-2030-says-rystad-energy/.

27 EPRI Battery Energy Storage System Incident Database. 2024. https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database.

28 *Difference Between Thermal Runaway and Fire Ignition of a Lithium Ion Battery*. EPRI, Palo Alto, CA: 2022. 3002025283.

SCENARIOS CONSIDERED

Selection of the BESS, location, and fire scenarios to be modeled will depend on the primary question being asked and potential human receptors of interest. Options to consider are listed below.

1. The scenarios may address multiple phases of battery fire events:
   - **Pre-Combustion (Off-gassing) Phase:**
     - Has the highest total gas release rate
     - Lasts seconds to minutes, or hours if a fire does not initiate
     - Density of the gases must be accounted for
     - Important to consider as 1) an increasingly common fire management approach is to keep the system in a pre-combustion stage while cooling, and 2) NFPA-69 Standard on Explosion Prevention Systems[29] compliant mechanical exhaust systems are designed to vent offgas before ignition
   - **Combustion Phase:**
     - Initial ignition can be explosive
     - Lasts hours
     - The combustion removes a large amount of the gases released
     - Dense gas effects can be neglected, but the buoyancy of the hot smoke needs to be accounted for
   - **Suppression Phase**
     - Chemical agents may be used by firefighters to stop the combustion, but the heat release continues
     - The emitted gases are lower than the pre-combustion phase but are not removed by combustion
     - Exposure of firefighters near the source becomes a consideration
     - Dense gas and buoyancy effects may both be needed
     - Water mist through rainfall or applied spray can substantially reduce concentrations of gases and particles through entrainment and dissolution
2. Concentrations should be calculated at 2 m and 1 m above ground level height at a minimum, as these bound typical human breathing heights. Concentrations at breathing heights can be lower than surface concentrations for dense gas thermal runaway events. Vertical profiles of the plume with additional points can be helpful in understanding exposure to people in closely sited multi-story buildings.
3. First responders may be more interested in the maximum distance away from the site at which concentrations can exceed health criteria than the exact concentration maps. This is easier to communicate, to use for decision-making, and to enforce for any evacuation and shelter-in-place orders implemented by the fire service managing the response.
4. Depending on emissions assumptions, HCl may be a larger health concern than HF for the combustion case. While the relevant health criteria (IDLH, AEGL) for HCl are higher than for HF, the larger emissions of HCl often lead to more exceedances of the health criteria. Any conditions resulting in concentrations protective of human health for HCl and HF is likely protective for all other pollutants of interest.

ADDITIONAL INSIGHTS

It could be helpful to have a simple meteorological station installed at the BESS facility. These can cost less than $1,000 and can be located at the height of the expected release point of a ventilation plume. The resulting wind speed and direction data can be used for proactive simulation modeling or during the response activities for an actual event. Most facilities currently must rely on city-wide meteorological stations, which can be located quite far in distance from the BESS and do not account for localized effects such as building structures.

Monitoring of the emitted pollutants from battery offgassing or a fire is another alternative. Portable monitoring devices (aka "gas detectors") for HF and HCl do exist in the range of several hundred dollars, but it is unclear if their lower detection limits or chemical specificity would be appropriate for a BESS incident. More complex monitoring devices such as open path spectrometers are substantially more expensive and require more power. With either type of device, equipment calibration and training on use would need to be determined.

29 National Fire Protection Agency 69 Standard on Explosion Prevention Systems. 2024. https://www.nfpa.org/product/nfpa-69-standard/p0069code.

KNOWLEDGE GAPS

Despite the increasing attention on air plume modeling of potential BESS failures, many knowledge gaps still exist that require future research and development. Critical review and assessment of options for emissions testing (both the experimental design and the instrumentation measuring the emissions) is the primary need. This capacity will improve understanding of fate and transport as the plume is emitted and evolves in the atmosphere. This topic is important as there is the capability of reaction and deposition of chemicals that are emitted from the battery in the enclosure itself or very near the source before the plume is fully evolved and migrates downstream. This issue will continue to be discussed in broad public forums as part of the development of the post-2023 edition of the NFPA 855 standard, as well as EPRI's forthcoming portfolio.

New ambient atmospheric concentration monitoring instruments can be quickly, easily and cheaply deployed during an actual failure event. Unmanned aerial vehicles (UAV) or drones have been outfitted with thermal cameras to image failure events; observe the evolution of thermal runaway and containment; and target water suppression activities in real-world BESS failure events. Another option to consider is the use of radar measurements of smoke plumes to measure plume rise.

UAVs have independently been outfitted with air quality monitoring equipment for greenhouse gases, NAAQS criteria pollutants (i.e., CO, $PM_{2.5}$, PM_{10}, NO_2, Pb, O_3, and SO_2), and hazardous pollutants. Combining these features into a single UAV system would allow for monitoring in and around off-gassing or combustion plumes in real-time, and the results could be fed into emissions and model evaluation studies, emergency response protocol development, and post-failure assessments. Determining what entity would best own and operate these devices would need to be determined in the future. Inclusion of a wider range of emitted chemicals (e.g., PM of specific composition, fire suppressant chemicals, and other organics) into modeling would provide broader insight into potential downwind consequences. It is also suspected that scaling emissions measured from module-level burn testing to a full unit fire introduces additional uncertainties which are not well-characterized. Use of UAV or other ambient monitoring during large-scale burn testing or real-world fires would help to resolve these concerns. Note that the commonly required Underwriters Laboratory (UL) 9540A[30] testing for BESS thermal runaway and flammability is not designed to measure emissions of toxics, and the necessary information cannot be gleaned from those test reports. Researchers are investigating chemical emission profiles, and their dynamics, from battery fires with a variety of analytical techniques and burn conditions.[31] However, these are generally based on module-only burns that must be scaled, with an unclear amount of associated uncertainty. Published studies also use a wide variety of methods which are not usually directly comparable.[32]

Detailed chemical evolution, phase changes, and deposition of gases and particulate matter released from BESS fires should be included in future plume modeling research. SCICHEM was chosen as EPRI's primary model partly because it can simulate these effects. For example, recent updates have included deposition effects[33] and suggest that simulated rain or water suppression (i.e., wet deposition) rates of as low as 3 mm/hr can reduce HF concentrations by an order of magnitude near the source and reduce HF transport downwind. This could be further explored by modeling water suppression scenarios and evaluating the potential counteracting effects of pollutant removal via wet deposition and the reduction of plume dispersion due to reduction in heat release and buoyant plume rise. Another recent update discusses the atmospheric chemistry of some key battery fire pollutants (e.g., fluorinated compounds, organic carbonates), which suggest significant chemical and deposition loss rates in typical ambient air conditions and makes recommendations for including this chemistry in air quality models.[34]

30 Underwriters Laboratory UL 9540A Test Method. https://www.ul.com/services/ul-9540a-test-method

31 *Lithium ion Battery Thermal Runaway Propagation and Emissions Analysis*. EPRI, Palo Alto, CA: 2021. 3002021644.

32 *Summary of Prior Electrochemical Battery Fire Emission Characterization Studies*. EPRI, Palo Alto, CA: 2020. 3002018741.

33 *Investigating Battery Fire Smoke Plume Dispersion: Effects of Deposition*. EPRI, Palo Alto, CA: 2022. 3002024677.

34 *Initial Addition of Chemical Evolution to Battery Fire Modeling Tools*. EPRI, Palo Alto, CA: 2021. 3002023295.

Finally, model intercomparisons are needed to understand if and how the designs and operations of each will result in varying ambient concentration results for similar scenarios and inputs. EPRI has recently completed a direct comparison between the FDS model and the SCICHEM tools.[35]

APPENDIX: EPRI'S EMISSION CALCULATION FOR RECENT BESS FIRE PLUME MODELING SCENARIOS

In EPRI's recent modeling, two calculations are performed. The first is for the total gas emitted, for which density effects need to be accounted. An emission factor of 0.1-0.7 L/Wh is used, which is multiplied by the size of the battery in Wh. The second calculation is for HF emitted. That is based on an emission factor of 0.4-1.5 g HF emitted/kg battery, which is then multiplied by the size of the battery in kg. In both cases all the gas and HF are assumed to be released in one hour. Thus, the HF emissions only depend on (a) the mass of the battery in thermal runaway, (b) the emission factor (g HF/kg battery) used, and (c) the assumption of how long the HF is released over.

If the emission factor for the total gas is changed, say from 0.4 L/Wh to 0.25 L/Wh, that reduces the total gas and changes the density effects. It does not change the HF calculation, just raises the percentage of the total gas that is HF. It could instead be assumed that a constant percentage of the gas is HF, but most scientific studies don't report their results that way, instead using mass (kg) or energy content (Wh) of the battery as the normalizing factor. If HF measurements from the 9540A testing that correspond to the lower gas release seen in the test are available, that could be used as an alternative emission factor.

35 *Comparing the Fire Dynamics Simulator and SCICHEM Plume Models for Battery Fires*. EPRI. Palo Alto, CA: 2024. 3002030364.

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

EPRI CONTACT

STEPHANIE SHAW, *Technical Executive*
650.855.2353, sshaw@epri.com

For more information, contact:

EPRI Customer Assistance Center
800.313.3774 • askepri@epri.com

3002030586 **July 2024**

EPRI

3420 Hillview Avenue, Palo Alto, California 94304-1338 USA • 650.855.2121 • www.epri.com