SUNNICA ENERGY FARM

EN010106

Volume 8

8.95 Applicant's response to the ExA's Third Written Questions

Planning Act 2008

Infrastructure Planning (Applications: Prescribed Forms and Procedure) Regulations 2009

03 March 2023
Revision 00

Planning Act 2008

**The Infrastructure Planning
(Applications: Prescribed Forms and
Procedure) Regulations 2009**

Sunnica Energy Farm
Development Consent Order 202[x]

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Planning Inspectorate Scheme Reference	EN010106
Application Document Reference	EN010106/APP/8.95
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Version	**Date**	**Status of Version**
Rev 00	03 March 2023	Deadline 7 Submission

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1 Introduction

1.1.1 This report responds to the Examining Authority's (ExA) third written questions, issued on 3 February 2023 **[PD-025]**. It responds to each of the questions posed to the Applicant. The Applicant has not responded to questions posed to specific Interested Parties but will review those responses once available and may comment on them at Deadline 8.

1.1.2 Section 2 of this report is tabularised to include the ExA's questions and the Applicant's responses to each question as follows:

- Principle and Nature of the Development (5 questions)
- Air Quality and Human Health (11 questions)
- Biodiversity and Nature Conservation (including Habitats Regulations Assessment) (13 questions)
- Compulsory Acquisition, Temporary Possession and Other Land or Rights Considerations (the ExA has no questions in this round)
- Cultural Heritage and Historic Environment (the ExA has no questions in this round)
- Draft Development Consent Order (dDCO) (2 questions)
- Environmental Statement – general matters (the ExA has no questions in this round)
- Landscape and Visual Effects (2 questions)
- Noise and Vibration (the ExA has no questions in this round)
- Socio-Economics and Land Use (15 questions)
- Traffic, Transport and Highway Safety (7 questions)
- Water Resources, Flood Risk and Drainage (2 questions)

2 Topic 3.0 - Principle and Nature of the Development

ExQ3	Respondent	Question	Applicant's Response
Q3.0.1	The Applicant	Decommissioning Should the ExA conclude that there would be likely to be permanent effects on the environment after decommissioning, despite the currently proposed post-decommissioning management measures? If the ExA does so conclude, why should it not require that the DCO secure effective regulation of the post-decommissioning environment?	The ExA should not conclude that there would be effects on the environment after decommissioning. The effect of the Decommissioning Environmental Management Plan (DEMP) will be to secure the restoration of the sites affected by the Scheme. Permanent environmental effects will be avoided. The loss of specific areas of vegetation will be substantially offset by new planting. SCC's case is primarily set out in **[REP6-077]** paragraph 3 and **[REP4-143]** paragraphs 9-11: i.e. that a loss of vegetation and trees should be considered permanent because what is lost is not "replaced on any secured, permanent and enduring basis". This is misconceived. First, with regard to loss of hedgerows, Paragraph 4.2.22 of the Outline Landscape and Ecology Management Plan (OLEMP) **[REP5-014]** sets out that the maximum hedgerow loss across the Scheme will be up to 1,068 m. This figure incorporates widening of entry and access points for large construction vehicles, creation of passing places on existing highways, internal access roads and trenching for internal cables and works along the grid connection corridor. However, paragraph 4.2.11 of the OLEMP **[REP5-014]** explains that on completion of construction, affected hedgerow sections will be reinstated in full. As illustrated by the Hedgerow Creation/Retained/Loss Status plan **[AS-326]**, the non-reinstated loss would be minimal across the Scheme, comprising the loss of small sections of hedgerow only, where this is required to facilitate access between fields. These small sections of loss are spread across the Scheme. This is not expected to result in any significant permanent impact on landscape, views or ecology. Furthermore, there will be a net increase in the amount of hedgerow of 6.332km by virtue of the OLEMP mitigation. In addition, none of the small sections of hedgerow to be lost benefit from existing protection that would prevent a landowner from removing them should they wish to do so in connection with their business or for any other reason. This means that there will be no permanent loss after decommissioning which could not have occurred absent the Scheme. The suggestion that there needs to be "secured, permanent and enduring" replacement goes beyond the Scheme's effects. Second, with regard to trees, as explained by paragraph 4.2.13 of the OLEMP **[REP5-014]**, the location of the Scheme would largely avoid the need for the

ExQ3	Respondent	Question	Applicant's Response
			removal of mature trees. It is nevertheless acknowledged that some tree removals and pruning of trees would be required. As set out by Tables 21 and 22 of the OLEMP **[REP5-014]**, the maximum total amount of tree canopy area that would be lost as a result of the Scheme would be 2.305 hectares. This maximum loss, which represents less than 0.25% of the area of the Sites, would be spread across a large geographical area and is not expected to significantly affect landscape or ecology. Paragraphs 4.2.26 to 4.2.27 of the OLEMP **[REP5-014]** explains that no veteran or ancient trees are to be removed and that only a small number of trees subject to a Tree Preservation Order (TPO) may be removed. These comprise part of three tree groups to the south of Worlington and two individual trees at Chippenham Road (east of Snailwell). The small amount of loss of trees and hedgerow is not expected to have any impact on landscape or ecology that warrants mitigation after completion of decommissioning. In any case, as noted in Tables 21 and 22 of the OLEMP **[REP5-014]**, the Scheme would create a net increase in the amount of hedgerow of 6.332km and a net increase in the amount of woodland of 50.44ha. This represents a substantial enhancement to green infrastructure, habitats and the landscape. The new hedgerow and woodland would establish and mature over the 40-year life of the Scheme. Should the woodland and hedgerow created by the Scheme be of sufficient value and quality that it warrants permanent protection, the appropriate statutory body would be able to designate and protect it appropriately in accordance with relevant legislation at the time. For example, TPOs could be made, and local nature reserves could be designated. Further, the Applicant has proposed amendments to the DEMP to allow for the assessment of the landscape and ecological value of features brought forward under the LEMP, and to consider means by which they may be secured in the long term. This is also the answer to the ExA's question as to how mitigation will be secured, if it should conclude that there will be permanent effects. First it must be recognised that there are discrete elements of landscaping and ecological mitigation which, once the Scheme has been decommissioned and removed, may look out of place. Second, the post-decommissioning environment is not known at this point. It is therefore appropriate for the DEMP to require the Applicant to set out which of the landscaping and ecological measures are of value and could be retained post decommissioning through the appropriate legal means at that time, such as TPOs. This approach is now included in the updated framework DEMP submitted at Deadline 7.

ExQ3	Respondent	Question	Applicant’s Response
Q3.0.2	The Applicant	Decommissioning Should the Applicant seek compulsory acquisition powers to enable it to discharge Requirements to address the post-decommissioning environment, and provide within the LEMP details of those measures and the areas of land to be included, taking account of the review process SCC has advocated in [REP4143]? If not please explain why not.	No. If agreement is reached for the land in question to be used for the lifetime of the Scheme under the terms of a lease, it would be a disproportionate interference with the rights of the owners to require the Applicant to permanently acquire land to secure ecological or landscape management after the Scheme has been removed, and after the land has been reinstated to the satisfaction of the relevant authorities under the terms of an approved DEMP. Given the Applicant cannot dictate how the freehold owner manages its land post the expiry of the lease term, the Local Authorities are effectively arguing that the Applicant is to ignore the voluntary agreements reached and compulsory acquire the freehold. This is not justified or proportionate and would also have implications for every other infrastructure and energy scheme in the country. Rather, the appropriate approach should be for the landscaping and ecological mitigation elements to be reviewed at decommissioning in the context of the post decommissioning environment and, if considered necessary, secured via the mechanisms available at the time, which could include TPOs and the like. Equally, there is nothing preventing the local authorities or other statutory bodies from using their statutory powers before the decommissioning phase. The Applicant has updated the FDEMP as identified in its response to Q3.0.1. The changes mean that the undertaker, at the point of seeking approval for the DEMP, will need to have discussions with the landowners and the local authorities to seek to address how any landscaping and enhancement measures that warrant preservation in the context of the decommissioning environment might be retained in the long term. The Applicant does not however think that CPO powers are required or justified for the reasons set out in its Written Summary of Oral Submissions at ISH2 7 December 2022 **[REP4-030]**.

ExQ3	Respondent	Question	Applicant's Response
Q3.0.3	The Applicant	Decommissioning We note your updated framework Decommissioning Environmental Management Plan (DEMP) [REP5-008] and updated Funding Statement (FS) [REP5-004]. With reference to paragraph 2.2.1 of the FS, please explain what the decommissioning of the proposed development will cost and how it will be funded; and Given the change in the ownership structure described in section 2.1 of the FS, please update the FS as necessary to ensure that it contains the most up to date information.	**How much will the proposed decommissioning cost** – cost estimates at this stage are inherently uncertain given the 40-year timeframe between now and when decommissioning will actually occur, and the effect intervening events will have on, say, equipment and other element costs. For this reason, developers estimate the decommissioning costs as a percentage of the expected upfront construction and equipment costs, but even that is inherently uncertain because of, for example, (i) the potential cost against cashflow 40 years into the future (so, the present value discount would make this a relatively small figure); and (ii) the ability to offset all or part of the costs from the sale of scrap material obtained from decommissioning the Scheme. Different financiers take different approaches to these various assumptions. However, one way the costs can at this point be calculated is as follows: An assessment might assume a % of the total upfront cost, which is currently estimated at c. £600m. The Applicant has used its professional opinion to calculate these values by assuming a proportion of costs as 12%, or £72m, minus the proportion of potential resale or metal scrap value at the time of decommissioning as 10%, or £60m. The resulting estimate is then equivalent to 2% of upfront cost, which is assumed to be £12m. It is important to note that this is very much an estimate and costs are indicative, and different financiers will take different approaches to these assumptions in their financial models. **How will this be funded** - The private landowner property agreements contain the (confidential) details which describe the mechanics of the decommissioning process including the security that needs to be put in place to cover the costs. The mechanics have been derived from past solar projects, whereby the Applicant must (at defined milestone points in time) create a form of security to finance decommissioning. This is paid for from Scheme revenues and the value is set by an independent expert to ensure at the end of project life there are ample funds to decommission. This ensures that sufficient funds are available and in-place well in advance of the final event of decommissioning.
Q3.0.4	The Applicant	Good design Further to your response to our ExQ1.0.5 and ExQ1.0.6, and in the light of any relevant submissions by Interested Parties, please comment on	In its answers to ExQ1.0.5 and ExQ1.0.6, the Applicant explained that the design approach for the Scheme has delivered good quality sustainable design through the strategic design decisions that have been made since an early stage in the Scheme, enabling the Scheme to respond to landform, local character and features. It goes on to explain that the good design that has been developed is secured via the

ExQ3	Respondent	Question	Applicant's Response
		the need for a DCO Requirement for a Design Champion and for a Design Council Design Panel review.	parameters that define the locations, maximum dimensions, nature, materials, and appearance of components of the Scheme. These are set out by the Works Plans **[REP6-006]** and the Design Principles **[REP6-037]** and are secured by the draft DCO **[REP6-014]**. In its answer to ExQ1.0.5, the Applicant also noted that a landscape architect would retain a role in the detailed design of the Scheme. To further enhance the detailed design process, the Applicant now proposes that a Design Champion would be appointed to a senior position within the Applicant's team. The Design Champion will have a background in landscape architecture and will work closely with the engineers and wider design team to ensure that the detailed design process takes opportunities to be as sensitive as practicable to the landscape and environment in which the Scheme is located, within approved parameters. This is secured in the OLEMP submitted at Deadline 7. The Applicant remains of the view that a Design Council Design Panel review would not be appropriate or beneficial, given that the design process is already well advanced, having been guided by professionals who have influenced the design from the earliest stage, including a team of landscape architects, and that the parameters that define the locations, maximum dimensions, nature, materials, and appearance of components of the Scheme are secured via the DCO.
Q3.0.5	The Applicant	Community benefit and legacy Further to your response to our ExQ2.0.1, we note that you say that you are *"in the process of developing a suite of further community benefits which it hopes will be enshrined in a planning agreement …"*. What are these? Do the relevant local authorities agree? and What is the real legacy of the proposed development for local people?	As outlined in the Planning Statement **[APP-261]**, the Scheme will deliver the following benefits: Decarbonisation: The Scheme will provide large scale contributions to the UK's decarbonisation and security of energy supply, while helping lower bills for consumers throughout its operational life. This will benefit the population of the country as a whole, including people who live locally to the Scheme. This is the fundamental benefit of the Scheme. Biodiversity Net Gain: The Scheme will deliver a substantial biodiversity net gain. Archaeology: areas of high value, which were not previously known, have been removed from the developable area of the Sites and will be preserved in situ. Increased Access: Incorporated into the Scheme design are also a number of permissive routes. These permissive routes will enable increased public access across the landscape of the local area and thus respond positively to local Green Infrastructure Strategies and local planning policies relating to rights of way.

ExQ3	Respondent	Question	Applicant's Response
			Soils and water: There are expected to be benefits for the soil quality of the land within the Sites. Much of the land within the Sites is currently in arable agricultural use which is heavily irrigated. The proposed grassland cover and the suspension of cultivation will provide a number of benefits to soil health including fertility, moisture retention and structural stability. The cessation of arable agricultural activities also has the potential to improve water quality due to the reduction in nitrate infiltrating the ground and entering watercourses. Employment: The Scheme will create significant employment opportunities during the construction phase. It is predicted that 1,685 total net jobs per annum will be provided directly and indirectly within the local economy during the two year construction period. The Applicant is also committing to implementing a Skills, Supply Chain and Employment Plan for the construction of the Scheme which will include provision of employment opportunities for local people. In addition to the above, the Applicant is committed to entering into a S106 agreement with the Local Authorities and discussions are ongoing as to its content. The S106 will provide funding for the following: £500,000 across both SCC and CCC for the creation of/or improvement of permanent Public Rights of Way and permissive paths. £140,000 for Stone Curlew Research. The Applicant is also in advanced discussions with the Cambridgeshire Community Foundation in relation to provision of a community benefit fund. However, as discussed at ISH4 this fund sits outside of the Examination and is not to be taken into account in the consideration of the Scheme. However, a substantial sum would be paid to the Community Foundation for it to invest in the community.

3 Topic 3.1 - Air Quality and Human Health

ExQ3	Respondent	Question	Applicant’s Response
Q3.1.1	The Applicant	BESS: future large solar farm projects What literature are you aware of that details the future development of battery storage solutions for large solar farm developments. If you are aware of any such, please provide succinct details and references.	Typically, free source literature covering innovation and design for solar projects tends to focus on PV technologies (solar panels) and technical grid connection logistics. Battery technology and energy storage system design developments often involve significant intellectual property from battery Original Equipment Manufacturers (OEMs) and BESS integrators meaning details are not usually capable of being shared before a full product launch. Battery cells or systems are not developed specifically for solar farms, cells tend to be developed for both EV and BESS applications with cell design tweaks and module design configuration for energy storage applications (this can include a range of renewable energy sources). Literature that focuses on battery designs and technologies for future energy storage systems tends to focus on medium to long term timeframes i.e. 2030 - 2050, which falls outside of the Sunnica design selection window and is not usually free source material. Systems that will be available for Sunnica are currently in production or are undergoing testing and will be certified in 2023 or early 2024. A good free source introduction and summary of a range of battery technologies for incorporation in future energy storage systems, is produced by the Atlantic Council’s Global Energy Centre, this has a US focus but covers systems costs, performance, supply chain issues and safety factors which are relevant to the UK (Alternative Battery Chemistries and Diversifying Clean Energy Supply Chains - Appendix 1). The US Department of Energy (US DoE) is leading the way in independent safety research and performance evaluation of battery technologies for grid scale energy storage. Their Grid Storage Launchpad opens in 2023 and will provide independent validation and real-world performance testing for the next generation of energy storage systems across a range of battery technologies (Appendix 2). Test data and conclusions will be publicly shared: https://www.pnnl.gov/grid-storage-launchpad-pnnl

ExQ3	Respondent	Question	Applicant's Response
			The Electric Power Research Institute (EPRI) is the other significant organisation conducting major research and testing for grid scale BESS design, EPRI is US based but has a global focus. Most research & safety materials are only available to members (utility companies, energy storage site owners & operators), however a variety of literature and data is released as free source materials through the Energy Storage Integration Council (ESIC), these include a significant range of guides, tools and templates that can be downloaded from the EPRI website: https://www.epri.com/pages/sa/epri-energy-storage-integration-council-esic?lang=en-US From a safety perspective EPRI focuses on immediate, near and medium-term research & development. The majority of case studies, research and safety solutions are scheduled for delivery within a 2-3 year development cycle. Key EPRI materials reviewed and incorporated into Sunnica safety planning are: • **BATTERY STORAGE FIRE SAFETY ROADMAP 2021** (Appendix 3 – submitted at ISH 3), the document clearly sets out a wide range of achievable design improvements for BESS. • **LESSONS LEARNED: LITHIUM-ION BATTERY STORAGE FIRE PREVENTION AND MITIGATION - 2021** (Appendix 4), the document summarises lessons learned from BESS incidents and BESS systems installed before key codes and rigorous significant scale safety tests were established. The report highlights how different modules integrating identical cells from the same battery OEM pose different fire & explosion risks. EPRI identifies the key safety toolbox they are developing from real world site operation assessments, large scale testing and validated consequence modelling i.e. not conducting risk assessments with extrapolated data from small scale battery testing. • **Proactive First Responder Engagement for Battery Energy Storage System Owners and Operators** (Appendix 5), the document maps out examples of best practice that the Applicant intends to integrate into the detailed design stage process. Best practice for engagement and BESS training with First Responders, Emergency Planning, Incident Management best practice, key site design features and required documentation are covered.

ExQ3	Respondent	Question	Applicant's Response
			Other major EPRI projects / resources / whitepapers in review or drafting stages which will likely impact on Sunnica design and safety planning are listed below together with EPRI project scope definitions. Many of the key safety issues raised during the DCO process are covered in these research topics and will be made available on EPRI's site: https://www.epri.com/research/programs/053125 • Considerations for ESS failure plume modelling – "how-to" guide for plume modelling will be developed to address the specific nuance and characteristics of ESS failures. • Emergency Response Plan Guidelines – development of a site-specific ERP for a member utility. A guidelines and template resource will be created to facilitate similar types of efforts. • EPRI Explosion Hazard Calculator V2 – specification guidance to support the sourcing of necessary information and update the explosion calculator tool for a combined set of resources for explosion hazard mitigation. • Safety Considerations for Specifications and RFPs – development of a guideline template addendum for specifications and RFPs that can be used by collaborative project members. • Community Engagement Guidelines – development of resources, checklist, templates and/or other material to help with community education and engagement on ESS projects. • HV Arcing Hazards During Battery Thermal Runaway - battery vent gasses are shown to reduce the insulation of air-gaps and other materials. This will be a testing case study exploration of those dynamics. • Resting SOC (State of Charge) Management for Operational Safety – there is data in literature about the lower TR hazards associated with lower SOC. What opportunities are there to operationalize that knowledge for pre-event planning (wildfire vs hurricane, etc). • Battery Thermal Runaway vs Fire Ignition Whitepaper – During a battery failure, there are two aspects of that event that are important to understand in relation to each other. The thermal runaway itself and the ignition that may occur.

ExQ3	Respondent	Question	Applicant's Response
			• Reference for Battery CT Scan Review – This resource is meant to give an initial guide and description to the types of internal defects that present themselves in CT imaging of lithium-ion cells. This reference can be used as a reference during RCAs or educational processes for energy storage teams. • Cell Chemistry Safety Whitepaper – "*stored energy is one definition of a hazard*" and regardless of chemistry, battery cells pose a hazard that must be understood and mitigated. Lots of examples on both sides of that debate for good (and bad) system design and integration. The LFP vs NMC debate often can miss the point and to say one chemistry is inherently "*safer*" can be misleading when looking at integrated systems. The UK National Fire Chiefs Council (NFCC) BESS planning guidance draft document is currently under consultation and will be published in 2023 (Appendix 6), recommendations will be fully observed and integrated into the Battery Fire Safety Management Plan. The NFCC document will be a key primary source in the drafting of the outline Emergency Response Plan framework and for compiling the comprehensive ERP which will be submitted as part of the Battery Fire Safety Management Plan. Powin & Jensen Hughes have just published a key collaborative paper on a performance-based assessment of an explosion prevention system for lithium-ion BESS (Appendix 7), this is a unique free source material insight into how UL 9540A test data and NFPA 69 explosion prevention standards can be used to ensure safer BESS designs. The battery systems integrate 280Ah LFP prismatic cells and demonstrate how CFD explosion consequence modelling from a venting thermal runaway reaction (non-burning) based on UL 9540A test data can validate gas exhaust system performance to NFPA 69 standards. Gas composition, cell propagation and gas release rates are defined. The Atkins BESS Hazard Assessment report for HSE Northern Ireland which has been referenced by Dr Fordham during the DCO examination process assesses the identical cell covered in the Jensen Hughes report. The Atkins calculations, assumptions and conclusions bear no relation to the reality of thermal runaway reactions generated from these cells during recent large scale BESS testing. Powin has conducted full scale free burn testing of their 750KWh Centipede BESS cabinet with both UL (9540A) and DNV (3rd party). Worthwhile fire risk assessment, explosion risk assessment and hazard mitigation analysis cannot be

ExQ3	Respondent	Question	Applicant's Response
			based around assumptions made about generic LFP and NMC battery chemistries. This is also reinforced by Fluence outdoor full scale free burn testing with UL (9540A tests) and DNV (3rd party testing) on their Fluence Cube system which integrates the same LFP cells into 52 cell / 46.6 KWh modules. The Cube integrates two battery racks with 8 modules per rack. Fluence recorded all the key fire (heat flux data, PHRR, module / rack temperatures, cell and module propagation times) and gas emission (flammable & toxic gases) data and started to publicly share data in February 2023: https://blog.fluenceenergy.com/battery-energy-storage-product-fire-safety-testing 26 cells were heated to produce a significant venting thermal runaway which continued for 5 hours before ignition of the gases. The Cube design maintained full structural integrity and burn / consumption time for two battery racks (746 KWh) took 6 hours. Propagation did not occur to adjacent Cubes with 7 inches spacing to the side and back with 7 feet front spacing to the next Cube container. Additional testing has been conducted to compile a comprehensive toxic gas emission report which will be released later this year. The Jensen Hughes report (Appendix 7) emphasises that UL 9540A test data is normally prevented from publication due to the fact that it integrates confidential data but it is critical to use specific battery system data to produce realistic conservatism for accurate hazard mitigation performance and risk assessment: "the *development of the source term, the extent and timing of thermal runaway propagation in the module and unit are used to construct an appropriate rate and duration of flammable gas release.* *Additional conservatism may be added to the source term to account for the various types of uncertainty present in this analysis. This includes test-to-test variability, the thermal runaway initiation method, and conditions compared to an actual scenario, as well as general experimental uncertainty. For example, different thermal runaway initiation methods can yield more or less released gas from the cell (Essl et al., 2020). To add conservatism to the source term, the actual cell release volume and gas composition are used in combination with a shorter time to propagate thermal runaway. This method results in a higher overall average gas release rate than using the overall timing from the UL 9540A*

ExQ3	Respondent	Question	Applicant's Response
			Test." As noted in the OBFSMP, the Applicant stresses that effective explosion prevention and protection systems for BESS containers is a non-negotiable core safety principle for Sunnica. SAFT the French lithium-ion battery manufacturer has conducted one of the most comprehensive BESS risk analysis & explosion testing programs for their battery systems and BESS container designs (Appendix 8), they shared this information to assist in the drafting of NFPA 855 (2023) to ensure that explosion prevention and protection is at the forefront of BESS design testing, validation and certification. The report defines gas release rates for SAFT cells in a variety of thermal runaway fire scenarios and contains a range of consequence modelling to validate BESS safety features. The report showcases test protocols and modelling procedures which are utilised as best practice by top tier battery OEMs and BESS integrators. There are several BESS designs undergoing testing and certification which are being subjected to even more rigorous full-scale free burn testing, significant scale gas capture, explosion testing and consequence modelling (heat flux, explosion prevention, toxic gas emissions) and will be able to provide a comprehensive quantification of thermal runaway events which consume a full BESS container. At the detailed design stage, the Applicant has committed to only considering designs which have been through the most rigorous test programs and can demonstrate that BESS battery system, container design, fire protection system and site spacing is validated through full performance testing. The Applicant's primary safety focus for Sunnica is one of incident prevention combined with comprehensive hazard mitigation solutions. There are several excellent BESS battery system predictive diagnostics products which are already integrated into BESS system control and monitoring software e.g. the Powin BESS system referenced in Appendix 7. If this type of data analytics is not automatically provided a BESS owner / operator has a right to be able to fully access and review battery system data. At the detailed design stage, the Applicant will ensure that BESS systems under consideration fully integrate additional data analytics to offer higher levels of Thermal Runaway protection to EMS / BMS controls. Appendix 9 is a white paper written by Accure who provide one of the industry leading BESS data analytics packages. The paper illustrates how existing battery faults, system faults, and

ExQ3	Respondent	Question	Applicant's Response
			operational faults can be quickly identified and describes how model-based diagnostics can be utilised to predict future safety incidents. The Sunnica fire safety team are involved in ongoing large-scale testing and validation programs for new BESS active cooling systems, detection products, suppression systems and dual explosion prevention & protection systems. Whilst product and safety design features cannot be publicly shared during the DCO hearings; lessons learned, test outcomes and product performance capability will be integrated into the BFSMP and referenced during the detailed design stage.
Q3.1.2	The Applicant, WSC, ECDC	BESS: relevant regulations Are you aware of any proposals before Parliament to bring specifically within scope of the relevant regulations large scale battery storage development for solar energy projects? If so please provide brief details.	The Lithium-ion Battery Storage (Fire Safety and Environmental Permits) Bill is currently before the House of Commons. The second reading of the Bill will take place on 24 March 2023. The Bill would dictate that industrial lithium-ion battery storage facilities are categorised as hazardous, meaning that the Environment Agency, the Health and Safety Executive and the local fire and rescue services would be statutory consultees when planning applications are considered. It is unclear whether the private members bill will be successful but the Applicant considers that the consultation and engagement it has undertaken for the Scheme has the potential to meet the requirements of the bill in any event.
Q3.1.3	The Applicant	BESS: COMAH and P(HS) regulations We note your response to our ExQ2.1.2 and ExQ2.1.3. Surely evolving technology will mean reduced impacts when the proposed development is constructed: that being the case, why do you not fix the design on that basis and commit through the DCO to obtaining authorisation under the COMAH regulations and hazardous substances consent?	The Applicant does not understand what is meant by "reduced impacts" - the impacts of the Scheme on the character of the area (landscape etc) have been fixed by virtue of the maximum parameters against which this DCO is assessed. If what is meant is a fixing of materials, as set out in the answer to ExQ2.1.3 BESS is a fast-evolving technology. Between the time of consent and the time of construction approved materials, methods of construction, and safety codes may well change. The Applicant cannot even commit to capping materials content because it is not possible to know what that will be without knowing the specific batteries in issue and reviewing their burn test data. As set out previously chemical content varies between batteries even within the same time (LFP or NMC) see [REP2-037] response to Q1.1.6. Fixing a detailed design at this stage would limit the flexibility that is required by the Scheme to allow the best use of land to be made.

ExQ3	Respondent	Question	Applicant's Response
			As to the final suggestion, the various regulatory regimes are of general application which will bind the Applicant or any other person. If, once detailed design is finalised, the regimes require a consent, the Applicant will need to obtain it. The ExA can assume that these other regimes will operate effectively. Accordingly, is wholly unnecessary and would be superfluous drafting to require in the DCO the Applicant to commit to complying with the COMAH regulations and obtaining HSC. Moreover, if, once detailed design stage is complete any COMAH authorisation or HSC is *not* required (and the Applicant acknowledges that various objectors do not think that would be the case), any commitment would require the Applicant to then do something it cannot do – obtain a consent it does not need.
Q3.1.8	The Applicant	BESS: emergency response plan We note the revised outline Battery Fire Safety Management Plan (BFSMP) submitted at Deadline 5 [REP5-050]. Please confirm that in paragraph 5.2.1 line 6 and elsewhere (eg paragraph 5.2.2 line 2) CRFS should read CFRS as an abbreviation of the Cambridge Fire and Rescue Service; and Appendices A and B are not listed in the table of contents and do not appear to be referred to: please explain what Technology 1 and Technology 2 are.	The Applicant can confirm that the correct acronym is CFRS rather than CRFS. The appendices A and B have been developed and included within the OBFSMP in response to requests from Interested Parties to demonstrate potential indicative layouts of the BESS areas. It is important to note that these layouts are indicative and subject to change but provide two versions of the potential configuration that would conform with the proposed Development Consent Order and the constraints including safety features as set out currently within the OBFSMP. The indicative designs were based upon BESS site design planning recommendations for first responders by the UK National Fire Chiefs Council, applicable statutory consultation requirements listed in Table 6 of the OBFSMP, and Table 13 containing complimentary Risk Mitigation Measures arising from the statutory consultation requirements. Key details contained in the site indicative plans are described in Section 2.5 General Arrangement. The safety features built into each of the layouts include: • A minimum of two access points to BESS sites (upwind from prevailing wind direction) • Impermeable membrane areas / drainage systems and bunded lagoon for safe containment of firefighting run off water • Lagoon access route for water tankers, allowing for safe analysis and extraction by tankers (if required)

ExQ3	Respondent	Question	Applicant’s Response
			• Emergency access routes around the perimeter of each BESS site, the roads are capable to carry FRS vehicles in all weather conditions with no overhead obstructions. • Multiple BESS observation areas for fire service at a safe distance (minimum of 30 meters from BESS containers) • Turning areas for FRS vehicles (complying with UK FRS stipulations) • 6-meter separation distances between containers and ESS equipment • Minimum spacing distance of 20 meters from BESS / ESS equipment to surrounding vegetation • Firefighting water tanks situated upwind from prevailing wind direction with a minimum spacing of 10 meters from the nearest BESS container Technology 1 corresponds with a potential solution currently in the market designed by Sungrow using containers housing batteries combined with a separate or independent power station. Each power station is composed of a power control system (PCS), a transformer (TX) and a switchgear (SG). The outline specifications align with the equipment and all fit within the Rochdale Envelope. Technology 2 corresponds with a potential solution currently on the market designed by Tesla using a cabinet structure housing batteries combined with a power control system (PCS) housed within a single cabinet. The transformers (TX) and switchgear (SG) stations are separate and aligned with a group of 2 cabinets.
Q3.1.9	The Applicant	BESS: final version of outline Battery Fire Safety Management Plan (OBFSMP) We note your response to our ExQ2.1.17, and in particular that the revised outline Battery Fire Safety Management Plan (BFSMP) now includes an independent fire protection engineer. Please explain	The Applicant apologises if its response to ExQ2.1.17 was unclear. For clarity: i) Ingress protection testing of BESS enclosures / containers is conducted under UL 9540 and / or IEC62933-5-2 certification for BESS systems. The OBFSMP commits to these test certifications. Typical BESS enclosure ingress protection levels are IP 55 / NEMA 3R or IP 66 / NEMA 4. IEC Factory Acceptance Testing or a 3rd party manufacturing audit which must be obtained by the BESS integrator

ExQ3	Respondent	Question	Applicant's Response
		i) why you would not conduct ingress protection testing, eg to IEC60068; and why you would not use data analytics to warn of maintenance or failure of components and/or systems.	assures that supplied BESS enclosures will comply with the requisite certified ingress protection levels. ii) The Applicant has committed to following the most stringent BESS electronic control and monitoring requirements, including data analytics. The OBFSMP commits to NFPA 855 and IEC 62933 standards which cover this area. The Applicant also stated that three new IEEE standards in development (IEEE P2686, IEEE P2688 and IEEE P2962) which cover data analytics, electrical controls and maintenance / replacement of battery components / systems, will be reviewed when published and included in the OBFSMP (if publication is before the detailed design process begins). If detailed data analytics is not automatically provided a BESS owner / operator has a right to be able to fully access and review battery system data. At the detailed design stage, the Applicant will ensure that BESS systems under consideration fully integrate additional data analytics to offer higher levels of Thermal Runaway protection to EMS / BMS controls.
Q3.1.11	The Applicant	Emergency response and evacuation planning We note your response to our ExQ2.1.19: your response indicates that major accidents and disasters assessment is required by the framework CEMP, OEMP and DEMP but that *"The final management plans must be in substantial accordance with the framework plans"*. i) What do you mean by "substantial"; and ii) how can those likely to be affected by major accidents and disasters have confidence in the final plans which will be agreed post consent?	(i) The Applicant has set out in response to First Written Question Q.1.5.67 **[REP2-037]** (see also responses to the same point in Questions 1.5.69, 1.5.71 and 1.5.73), why the use of the term "*substantial*" is necessary in the context of a detailed / final plan being in accordance with a framework or outline plan. The response to that question explains that without the term "*substantially*", "*in accordance with*" could be construed as meaning exactly the same as. This is not appropriate in this context as the framework plans set out the framework or outline for the final management plan, which will be developed based on the detailed design of the Scheme and any updates in legislation or guidance. It is therefore important that the term "*substantially*" remains as part of requirements associated with final / detailed plans to be submitted in the future, in order to build in the flexibility needed for the plan to be developed in accordance with the greater level of detail that will be known at a later stage. A requirement for the detailed CEMP, OEMP and DEMP to be "*substantially*" in accordance with the relevant framework plans demands a high level of consistency – the substance of the detailed plans must be in accordance with their outline versions. This means

ExQ3	Respondent	Question	Applicant's Response
			that the key elements of these plans, including the mitigation measures secured, must be included in the detailed plans. Critically, however, the chosen drafting provides sufficient flexibility for certain aspects of the detailed plans to be developed and/or differ slightly from the outline versions, should this be required in order to respond to unforeseen variances or advances in technology, for example. (ii) People can have confidence in the final plans given the response to (i) above, which confirms that the substance of the detailed plans would accord with their outline versions. They can have further confidence knowing that (rather than being "*in accordance with*" which essentially means "*the same as*"), there is the ability for, and expectation that, the certain aspects of the final detailed plans will be further developed to respond to the detailed design of the scheme, the technology employed and the very latest legislative and regulatory requirements, meaning that the plans and measures in place will be set up to respond to the specific set of circumstances for the scheme at the time.

4 Topic 3.2 - Biodiversity and Nature Conservation (including Habitats Regulations Assessment)

ExQ2	Respondent	Question	Applicant's Response
Q3.2.1	The Applicant	Framework CEMP [REP5-044] Tables 3-4 and 3-5 do not appear to show the commitment to position all drainage to avoid the area of constraint associated with retained trees. Will this be rectified? if so, please explain how this will be secured within the framework CEMP.	Table 3-5 of the Framework CEMP **[REP5-044]** (see page 16C-35, paragraph 7) states: "*All drainage proposals will be designed to avoid the RPA of trees to be retained".*
Q3.2.2	The Applicant	Framework CEMP [REP5-044] How would performance of the detailed Arboricultural Method Statement be secured in the framework CEMP and DCO? Please include reference to WSC's comments on the pre-construction bat survey in its D6 submission [REP6-080].	The FCEMP **[REP5-044]** page 16C-36, paragraph 4 includes a commitment to implement the results of the Arboricultural Method Statement as underlined in the extract below: *"A pre-construction tree survey will be undertaken where construction works are likely to affect trees. The findings of this will be included within an Arboriculture Report, which will be accompanied by a detailed Arboricultural Method Statement which will set out mitigation and protection measures to be undertaken. These reports will build on the PAMS provided in Appendix 10B of this Environmental Statement [APP-101] and the Arboricultural Impact Assessment [EN010106/APP/8.46]. <u>The findings and recommendations of these will be taken into account carried out and implemented by the appointed contractor."</u>* The performance of the detailed Arboricultural Method Statement will be managed via an auditable system of site monitoring as indicated by the PAMS, Section 1.5 (Appendix C of the Arboricultural Impact Assessment Report **[APP5-052]**) which states: *"An auditable system of site monitoring shall be established to guide contractors on site to ensure that tree protection measures are implemented and adhered to.* *This includes site visits by the appointed Arboriculturist to confirm the correct installation of protective fencing, to oversee sensitive elements of works within the Root Protection Areas (RPAs) of retained trees, to review the suitability and*

ExQ2	Respondent	Question	Applicant’s Response
			stability of retained sections of tree groups following removals and to sign off the Scheme when works are completed and tree protection fencing can be dismantled.” The Arboricultural Method Statement will include finalised details of site supervision and monitoring and this will be submitted to the Local Planning Authority. The following commitment, as set out in the Applicant’s response to LPA Deadline 4 Submissions **[REP5-057]** and WSC’s Deadline 6 submission **[REP-080]**, has been added to the Framework CEMP for Deadline 7: *‘Following the provision of the detailed Arboricultural Method Statement and prior to the commencement of any tree works, where necessary, further inspections for bats will be undertaken. This would include updated roost assessment, presence or likely absence survey (e.g. tree climbing and/or dusk emergence) and if necessary, the obtaining of a mitigation licence for the proposed works where impacts to roosts are identified’.*
Q3.2.3	The Applicant	Framework CEMP [REP5-044] Will pre-commencement surveys for bats now be included in the CEMP following WSC’s comments at D5 in response to the Applicant’s summary of submissions made at ISH2 [REP4-030]?	In their response at Deadline 5 to the Applicant’s summary of submissions made at ISH2, WSC stated, *‘the Councils cannot find any reference within the CEMP to the requirement for pre-commencement surveys for bats.’* The Applicant can confirm that this commitment is included within Table 3-3 under the ‘Monitoring Requirements’ heading (pages 16C-13-16C-15) of the Framework CEMP **[REP5-043]** and states: ‘*Updated species surveys, including bats, great crested newt, breeding birds, otter, water vole and badger, will be completed as appropriate to re-confirm the status of protected species identified, to inform mitigation requirements and support protected species licence applications, if required by Natural England.* *Such surveys will be undertaken sufficiently far in advance of construction works to account for seasonality constraints and to allow time for the implementation of any necessary mitigation, prior to construction. Additional surveys may be required during the advance works, site clearance and construction phase as advised by the ECoW team, based on the findings of the updated walkover and protected species surveys, or otherwise as identified as appropriate by the Applicant or their appointed contractor.’*

ExQ2	Respondent	Question	Applicant's Response
Q3.2.4	The Applicant, the LPAs	Ecology working group How is it proposed to continue to fund the Ecology Working Group, including funding work undertaken by that group?	As set out in its other submissions, the Applicant considers that it is required to fund the Ecology Advisory Group as a consequence of it being required to be put in place and maintained by the OLEMP, and compliance with the OLEMP being secured by the DCO. Updates have been made to the OLEMP at Deadline 7 in this regard.
Q3.2.5	The Applicant	ISH2: correction Paragraph 3.6.1 of your written summary of oral submissions at ISH2 [REP4-030] refers to the “Morten review”. Please correct this so that it reads “Lawton review”.	The Applicant agrees that this should read ‘Lawton review’ and that the submission can be read corrected as such.
Q3.2.6	The Applicant	HRA: dust monitoring Please respond to CCC points [REP4-137] regarding dust monitoring for the Molinia feature at Fenland SAC.	The Applicant responded to this point in the Deadline 5 submission ‘Applicant’s response to LPA Deadline 4 Submissions’ **[REP5-057]**, stating: ‘*Locations for proposed off-site daily inspections will be confirmed post-consent in the Dust Management Plan that will form part of the CEMP – this has been made clearer in the FCEMP submitted at Deadline 5.’* Table 3-9 of the Framework CEMP **[REP5-043]** states the following for dust monitoring: ‘*Undertake inspection, where receptors (including roads and ecological receptors) are nearby, where access is granted to monitor dust, record inspection results, and make the log available to the local authority when asked. This should include regular dust soiling checks of surfaces within publicly available land within 100m of Order limits, with cleaning to be provided if necessary.’* Further to this, the Applicant will include this monitoring provision within Table 3-3, to clarify that specific inspections will also be undertaken of relevant *Molina* communities within Chippenham Fen (Fenland SAC) and that details of locations will be finalised in the detailed CEMP, which will be subject to approval by CCC.

5 Topic 3.5 - Draft Development Consent Order (dDCO)

ExQ2	Respondent	Question	Applicant's Response
Q3.5.1	The Applicant, ECDC, WSC	Fees schedule and related matters How would the DCO be amended, with possible reference to Schedule 13, paragraph 2, to incorporate an eventual Fees Schedule for the discharge of Requirements in the DCO? What further changes are necessary or desirable to the proposed wording set out by WSC in its Deadline 5 submissions? How would a commitment by the Applicant to pay, prior to commencement, a contribution towards enforcement monitoring during the lifetime of the proposed development be best secured? Are there any significant examples, of which the District Councils or the Applicant are aware, of monetary commitments set out in plans certified in a DCO, where a dispute has arisen and was resolved through enforcement of the relevant DCO Requirement?	• The Applicant has included in Schedule 13 of the draft DCO a placeholder for the Fees Schedule relating to the discharge of requirements and it will include in the draft DCO to be submitted at Deadline 10 its position on the Fee Schedule, which is currently set out at Appendix B to this document. • The Councils' proposed fee schedule, and the rationale behind it, is not accepted by the Applicant. • The Applicant does not consider the Sizewell DCO to be an appropriate starting point for consideration of fees payable as part of this DCO. The nature and scale of the development, and the inherent complexities of delivering a nuclear power plant and associated infrastructure, means that Sunnica Energy Farm and Sizewell C projects do not have comparable design requirements. The most comparable recently made DCOs to the Sunnica project are Cleve Hill and Little Crow, which would be more appropriate precedents for this DCO. Importantly, neither of the DCOs for these projects include provision for the payment of fees to accompany submissions to discharge Requirements. Notwithstanding the precedent from the only two made solar DCOs, the Applicant is willing to agree a charging schedule for the discharge of Requirements, provided that the fees are appropriate, reasonable and justified. The Applicant agrees that the Town and Country Planning (Fees for Applications, Deemed Applications, Requests and Site Visits) (England) Regulations 2012, (as amended) (the Fee Regulations), are a sensible starting point for fees, but notes that they do not apply to DCOs generally and the therefore considers that it is inappropriate to apply them wholesale.

ExQ2	Respondent	Question	Applicant's Response
			Requirement 6 is not comparable to a reserved matters planning application for a solar farm, and therefore the Fee Regulations category that would apply to the first reserved matters application for a solar farm (erection of plant and machinery) is not suitable for use in the DCO. This is because the DCO will specify the approved locations, maximum parameters and (where applicable) materials and finishes, for all elements of the Scheme. The Scheme will be able to be delivered in any way that is compliant with the locations, parameters and details approved by the DCO. The Councils' role in considering Requirement 6 will therefore be limited to the following: a. Checking that the details proposed accord with the parameters approved by the DCO, including: i. Works Plans ii. Design Principles iii. Flood Risk Assessment iv. Battery Fire Safety Management Plan b. Checking that the design has taken account of the arboricultural impact assessment or updated tree surveys. It is clear that the intention in the Fee Regulations for the calculation of fees for solar schemes did not envisage projects of this scale, as they are for projects consented under the TCPA 1990 route, rather than those above the threshold for nationally significant infrastructure projects. The Applicant also does not accept that the fee for Requirement 6 should be based on site area. The size of the land to which the application relates does not relate proportionally to the complexity of discharging the requirement. For example, design details of proposed structures will be the same across the Scheme and will not require consideration more than once. The Applicant broadly proposes a £116 fee for most requirements, with a £2,082 fee for design requirements and a £462 fee for re-approval of design Requirements. A proposed fee schedule setting this out is included as an Appendix B to this document.

ExQ2	Respondent	Question	Applicant's Response
			• The Applicant has considered the Councils' request for money to fund enforcement and does not consider that it is appropriate or necessary to pay an allowance to the Councils for enforcement, which is a statutory duty on the Councils. The CEMP and DEMP will set out clear and straight-forward parameters for the construction and decommissioning of the Scheme, which will be secured by the DCO making it a criminal offence for the undertaker to not comply with the provisions of the CEMP and DEMP. The fact that a development may face a level of opposition amongst some of the local population is not considered a reasonable justification for a demand for funding of enforcement. • The Applicant is not aware of any relevant examples of monetary commitments set out in plans certified in a DCO where a dispute has arisen and was resolved through enforcement of the relevant DCO Requirement.

6 Topic 3.7 - Landscape and Visual Effects

ExQ2	Respondent	Question	Applicant's Response
Q3.7.1	The Applicant	Photomontages In relation to the Verifiable Photomontages [APP-220 to APP-232] please state the notional size of the solar panels portrayed in the photomontages.	The tops of the solar panel arrays portrayed in the photomontages are shown at 2.5m above ground level, which is the maximum height specified in the Design and Access Statement [**REP3A-032**].
Q3.7.2	The Applicant, SNTS	Photomontages The Verifiable Photomontages from Viewpoints 11, 11b, 12a, 14, 18, 25, 32, 33 and 46 [APP-221; APP-222; APP-223; APP-224; APP-226; APP-227; APP-228; APP-229 and APP-232] appear to show summertime planting superimposed on wintertime landscapes. Please comment on the extent to which you consider that these photomontages give an accurate representation of the effects of mitigation planting during the winter.	The photomontages are supporting material to the landscape and visual impact assessment (LVIA) summarised in Chapter 10 of the Environmental Statement **[APP-042]**. The assessment scenarios they inform are Scheme operation Year 1 (winter), representing a worst-case scenario, and Scheme operation Year 15 (summer), representing the established proposed planting in summer to reflect the seasonal change. This is described in the LVIA **[APP-042]** paragraphs 10.3.10-0.3.11, and 10.4.22-10.4.23. The verifiable photomontages from Viewpoints 11, 11b, 12a, 14, 18, 25, 32, 33 and 46 **[APP-221; APP-222; APP-223; APP-224; APP-226; APP-227; APP-228; APP-229** and **APP-232]** give an accurate representation of the effectiveness of mitigation planting during winter in the Year 1 scenarios. The Year 15 scenario photomontages represent the Scheme with proposed mitigation during summer once it has established. Due to the timing of viewpoints being finalised and seasonal constraints the mitigation planting is superimposed on a winter baseline photograph in these photomontages. Therefore, in such cases it can be assumed that where existing deciduous vegetation is located between the viewpoint and the Scheme, it would be more effective in screening views in summer than is shown in the photomontage.

7 Topic 3.9 - Socio-Economics and Land Use

ExQ3	Respondent	Question	Applicant's Response
Q3.9.2	The Applicant	Consolidated access and PRoW plans We note your response to our ExQ2.9.13. Please advise when the consolidated set of Access and Rights of Way plans will be submitted.	The Access and Rights of Way Plans were updated at Deadline 6 **[REP6-007]** which included the Permissive Routes proposed by the Scheme and the PRoWs which interacted with those routes; however, the ARoW have been updated at Deadline 7 to include all PRoWs within the vicinity of the Scheme.
Q3.9.3	The Applicant	Consolidated access and PRoW plans Will the Applicant, before submitting a consolidated set of access and public rights of way plans, have discussed this with LHAs as well as LPAs, notwithstanding the Applicant's current position on NMUs as noise receptors? If not please explain why not.	The Applicant has discussed the consolidated plans with the LHAs and the LPAs. The Applicant confirmed with the LPAs in a meeting on the 9th of February that they had no further concerns regarding these plans.
Q3.9.6	The Applicant	Fordham Walking Group concerns Will Fordham (Cambridge) Walking Group be included as a consultee in the FCEMP [REP5-044] and if not why not?	The Fordham Walking Group will be included as a consultee in the Framework CEMP.
Q3.9.7	The Applicant	Additional spurs on circular path at E05 Will the revised Environment Masterplan [REP-061] be updated to include an additional spur to Beck Road, and one to the northern edge of the site as requested by CCC in relation to E05? If not please explain why not.	The Environmental Masterplan has been updated at Deadline 7 to include the additional spurs to the permissive path south of E05 to connect with Sheldrick's Road and Beck Road east of Isleham.
Q3.9.8	The Applicant	Sectional drawings Please explain where in the application documents sectional drawings show	The Applicant has produced Site Access Drawings for all interactions with the highway verge. These are shown in Appendix C 1-7 of the Construction Traffic Management Plan and Travel Plan and were updated at Deadline 5 [**REP5-021 - REP5-034**]. No detailed design has taken place, but the Applicant has

ExQ3	Respondent	Question	Applicant’s Response
		accurately verges that are part of the highway and whether you have engaged effectively with the local highway authorities to use highway boundary data to provide the examination with this information. If not please explain why not.	demonstrated the feasibility and safety of the accesses and also notes paragraph 3 of the Local Highway Authorities Protective Provisions [**AS-319**] requires their approval of that detailed design. The Applicant has engaged regularly with the local authorities to discuss their interests within the Order limits, this has included discussions regarding highway boundary data. Polygon data has not been provided to the Applicant; however, discussions are ongoing and the Applicant is presently working with the local authorities to resolve any outstanding queries, with requests having been formally submitted by the Applicant on 3 February and 15 February 2023. This is considered in more detail from paragraph 6.1.22 of the Written Summary of Applicant’s Oral Submissions at the Issue Specific Hearing on Environmental Matters on 16 and 17 February 2023. With regards to the current determination of the highway boundary, this has been assessed using a combination of polyline data, land registry data, OS mapping boundaries, street view imagery and select site visits.
Q3.9.9	The Applicant	Shared use of accesses Please explain where in the application documents it is clearly explained, including by means of a plan or plans, how site and cable route accesses would be shared with agricultural, commercial, or domestic traffic during construction and operational stages of the proposed development, with a clear explanation of how conflicts will be managed. If this information is absent, please explain why.	The cable route will be constructed over a six month period between months 2 and 7, as set out in Table 2.1 of the Framework Construction Traffic Management Plan and Travel Plan [**REP5-015**]. It is not possible at this stage of the project to specify how long each of the accesses will be in use for construction over this period, but it is expected to be for less than six months. During the construction phase, temporary traffic management measures will be in place to ensure that the addition of Sunnica traffic can be accommodated safely. Right of access will be retained for any existing uses and landowners on the site during the period in which the temporary traffic management is in place, and this will also be facilitated through the Temporary Traffic Management. The access arrangements from the public highway ensure that there will be no conflict between users. Internal site layouts will ensure that work sites are suitably controlled without unauthorised access. Following the construction of the cable route, i.e. for the remainder of the overall construction phase and the operational and decommissioning phases, the accesses used will be reinstated to their current form and will be used as they currently are. There will be no requirement for Sunnica LGVs or HGVs to access the cable route sites, unless a fault is identified remotely. If a fault is identified, the Applicant will be required to agree access arrangements with the LHAs to ensure safe and suitable access. If required, the DCO powers enable the Applicant to re-introduce the temporary traffic management measures (with the consent of the

ExQ3	Respondent	Question	Applicant's Response
			traffic authority concerned) applied during the construction phase. This provides confidence that safe and suitable access can be achieved in any eventuality. The Applicant recognises the questions raised by the Examining Authority and LHAs in understanding the usage of each access. To provide clarification overall, the Applicant has prepared a table clearly setting out existing uses of each access, and proposed uses during construction, operational and decommissioning phases. This includes the level of existing usage retained during each phase. This Table is Appended to this document.
Q3.9.10	The Applicant	NMUs Will the Applicant now accept that NMUs should be assessed as noise receptors? If not please explain why, having regard to the local authorities' concerns expressed in their Deadline 6 submissions, for example CCC's Comments on Applicant's Response to ExQ2, Q2.9.9, page 72.	We agree that NMUs are noise sensitive receptors and that noise can detrimentally affect NMUs. Noise is assessed based on the effect on health and quality of life. Noise generated by the Scheme will only affect NMUs for limited periods of time when they are in close proximity to the noise source and, for the majority of the time, NMUs will continue to be able to enjoy the countryside. NMUs may feel noise is detrimental to their experience during the period of exposure, but the overall quality of experience is unlikely to be diminished. It is acknowledged that short-term exposure to construction noise can cause disturbance to NMUs and result in adverse noise effects. Planning Practice Guidance Noise identifies an adverse noise effect as *"Affects the acoustic character of the area such that there is a small actual or perceived change in the quality of life*." This is considered to describe the level of noise effect that may be perceived by NMUs. However, given the linear nature of PRoWs, the range of noise impacts along them and the transient usage of a PRoW by NMUs, a material change in the experience of using the PRoWs as a whole, which could affect NMUs health or quality of life, is not anticipated. As set out in Chapter 11: Noise and Vibration of the Environmental Statement [**APP-043**], no significant adverse effects on PRoWs have been identified as arising from the Scheme. The Noise Policy Statement for England provides a means for noise effects to be identified. It allows for adverse effects on health and quality of life to occur given that all reasonable steps have been taken to reduce these effects whilst taking into account sustainable development. In accordance with the Noise Policy Statement, the Applicant has taken all reasonable steps to manage potential noise impacts on NMUs during the construction, operational and

ExQ3	Respondent	Question	Applicant's Response
			decommissioning phases of the Scheme. These are set out in the Framework CEMP, which sets out best practicable means, as defined in Section 72 of the Control of Pollution Act 1974, of managing noise impacts. Table 3-6 of the Framework CEMP sets out the mitigation measures for the Scheme in relation to construction noise and vibration. Noise limits, noise monitoring and any additional mitigation measures to control noise impacts on NMUs would be agreed with the host authorities and secured through the Section 61 process.
Q3.9.11	The Applicant, CCC, SCC, WSC, ECDC	Enhancements to the PRoW network Please summarise, with reference to relevant policy statements or guidance if considered relevant, your understanding of how, if at all, the ExA may or should take account of the extent to which a section 106 obligation or obligations completed by the end of the Examination would meet concerns expressed by IPs for the need for the proposed development to incorporate enhancements to the PRoW network. In your response, please include what account may or should be taken by the ExA in its recommendation report in the event of any proposed party failing without reasonable excuse to make good progress to complete the same.	The Applicant's position with respect to the Scheme's likely impact on the users of the PRoW network is as set out in Chapter 12 of the Environmental Statement [APP-044], and is that there would be a minor beneficial effect during operation of the Scheme. The Applicant has incorporated four new permissive paths as part of the Scheme (and the Applicant has been clear as to the reasons why it cannot commit to those paths being permanent PRoWs, given that landowners hosting the Scheme do not agree to PRoWs on their land, and in any event the Scheme will be decommissioned after 40 years and there would be no ongoing effect to mitigate after that time). However, the Applicant recognises the position of the local authorities as set out in the joint Local Impact Report and in subsequent submissions and hearings, that the Councils do not consider that the permissive paths proposed as part of the Scheme adequately mitigate/compensate for the disruption to the existing PRoW network, and that therefore opportunities for ProW improvements, and new ProW/permissive paths during operation of the Scheme should be further explored in order to allow for mitigation for residual amenity impacts and/or legacy benefit. It is in this context that the Applicant and the County Councils have actively engaged with respect to an appropriate planning obligation towards improvements to the PRoW network. The Applicant has proposed a contribution in the amount of £500,000 to fund a package of public access mitigation strategy measures, comprised of enhancements to existing PRoW, creation of new PRoW or permissive paths, and upgrading or providing new connectivity points for users of PRoW or permissive paths. It is the Applicant's understanding that this contribution potentially would address the concerns raised by the Councils in terms of impacts to the PRoW network, however, the Applicant is still in discussions with the Councils as to the details of how the contribution could be

ExQ3	Respondent	Question	Applicant's Response
			spent, and so this position cannot yet be confirmed. The key outstanding point of discussion between the parties relates to the areas where the contribution could fund an order to create a new PRoW (that is, without landowner agreement). The Applicant is somewhat restricted as to what it can agree in this respect, in order to ensure it does not breach the voluntary agreements it has reached with landowners (as required in order to minimise the use of compulsory acquisition powers). The Applicant notes in this respect, that the purpose for which the contribution could be utilised by the County Councils would in no way prevent them from making a creation order to create a new PRoW on landowners' (i.e. those landowners with an interest in the Sites) land, the restriction the Applicant requires is that the contribution could not be used to fund the process required to secure such an order (or pay compensation in relation to it). The Applicant considers, taking both the permissive paths to be provided as part of the Scheme as well as a considerable contribution towards new or improved PRoW and permissive paths in the vicinity of the Sites, that it has done what it can to create enhancements to the PRoW network in connection with the Scheme. The Applicant and the County Councils are endeavouring to complete the legal agreement to secure the planning obligations. The agreement has been heavily negotiated, and the Applicant currently anticipates that execution and completion of the agreement prior to the end of the Examination is achievable.
Q3.9.12	The Applicant	Public and private roads The ExA considers that in the interests of clarity Schedule 5 parts 1 and 2 of the DCO should be updated to clarify which roads are public and which are private, and whether the works referenced in column (3) would take place on public or private sections of the roads listed in column (2).	The Applicant will provide for this in the next version of the dDCO being submitted, albeit this will be achieved through amendments to the existing table rather than including an additional column.

ExQ3	Respondent	Question	Applicant's Response
		Does the Applicant agree? If so, please provide the necessary amendments within the next iteration of the DCO.	
Q3.9.13	The Applicant	PRoW closures Are the amendments proposed to the DCO and CEMP to ensure that PRoW would only be closed as a last resort, as included in CCC's response to 8.81 Public Rights of Way Closure Note [REP-068], acceptable? If not please explain why not.	The Applicant does not consider that it would be appropriate to refer to "last resort" in the draft DCO. The rationale for this is considered in more detail in the Written Summary of Applicant's Oral Submissions at ISH4 on 16 February 2023 submitted at Deadline 7. Nonetheless, the Applicant has made amendments to the Framework Construction Traffic Management Plan (updated for Deadline 7) in respect of this issue – see paragraphs 6.3.4 and 6.3.10 – in light of comments made by Cambridgeshire County Council.
Q3.9.15	The Applicant	PRoW closure note Does the Applicant agree with the wording of the proposed amendments to the DCO, Articles 11(1), 11(3), 9(1)(b), Schedule 2, Requirement 16 provided by CCC on behalf of itself and SCC in its D6 submissions, together with the amendments to the CTMP? If not please explain why not.	The Applicant's position on these provisions and the proposals put forward are set out in section 7 of the Written Summary of Applicant's Oral Submissions at ISH4 on 16 February 2023 submitted at Deadline 7.

8 Topic 3.10 - Traffic, Transport and Highway Safety

ExQ3	Respondent	Question	Applicant's Response
Q3.10.1	The Applicant	CTMP and TP [REP5-015] We refer to your response to our ExQ2.10.12, to the updated Appendix 13C Framework CTMP and TP [REP5-015] and to the updated drafting of Requirement 16 in the draft DCO: to avoid confusion, please confirm that the cover sheet status column of the updated Appendix 13C Framework CTMP and TP [REP5-015] should read "Deadline 3A" for Rev 03 dated 28 November 2022; and the updated Requirement 16(3) should read (ExA emphasis) "*(3) No part of the permitted preliminary works for each phase comprising above ground site preparation for temporary facilities for the use of contractors, the diversion and laying of apparatus and site clearance (including vegetation removal, demolition of existing buildings and structures)* ***may commence*** *until a permitted preliminary works traffic management plan for that phase has been submitted to and approved by the relevant county authority for that phase or, where the phase falls within the administrative areas of both the*	That is correct. The Applicant confirms that the draft DCO will be updated to add 'may start' rather than 'may commence' as requirement 16(3) relates to permitted preliminary works so are outside of the definition of commence.

ExQ3	Respondent	Question	Applicant's Response
		county of Suffolk and the county of Cambridgeshire, both relevant county authorities."	
Q3.10.2	The Applicant	CTMP and TP [REP5-015] Please clarify in your response to D4 submissions [REP5-057] whether use of cable route site accesses would occur through routine inspection or the like, and please explain the reference to "the same Temporary Traffic Measures", as it is unclear how this would be possible, practicable, or desirable.	The Applicant can confirm that there will be no routine requirement for operatives of the Sunnica Energy Farm development to utilise any of the cable route accesses during the operational phase. The only requirement for access will be if there is a fault identified. Monitoring to ensure that the cable routes are working appropriately will be undertaken remotely. Any faults would be identified through this process. The Applicant considers that the cable route accesses are safe and suitable, with the introduction of Temporary Traffic Management measures under article 44 of the draft DCO [**REP6-013**], during the short period of intensification during the construction phase. If there is a requirement to use the cable route accesses in the operational phase, as a result of a fault being identified, the draft DCO also provides for the Applicant to introduce relevant Temporary Traffic Management Measures (also article 44), with the consent of the relevant traffic authority. This would ensure that safe and suitable access is achieved during any such short period of usage within the operational phase. The use of these accesses, and introduction of Temporary Traffic Management, would be discussed and agreed with the LHAs if the need arises.
Q3.10.3	The Applicant	CTMP and TP [REP5-015] Please (i) explain where in the application documentation it is clear what vehicle movements or management during the operational phase have been considered, such as at Sunnica West Site A, Access A; and (ii) please provide a clear explanation, by the use of plan or plan(s) and drawings, of how safe access can be established at this site, without significant removal of foliage at both sides of the junction.	Section 4.1.9 of the Framework Construction Traffic Management Plan and Travel Plan [**REP5-015**] describes the use of each access during construction, operation and decommissioning. This sets out that Sunnica West Site A, Access A will be used as the main access to the construction car park and operational staff car park. This question relates to the operational phase. As set out in paragraph 5.2.1 of the Transport Assessment [**APP-117**]**,** there will be a total of 17 staff required on site on a daily basis for the whole scheme during the operational phase. Staff will be split across the two operational phase car parks, but even assuming that all staff travelled by single occupancy vehicle, and all staff went to the same access, this would still only equate to 17 car journeys inbound at the start of the day, and outbound at the end of the day. Staff in LGVs will on occasion travel between sites during the day during the operational phase. There will be no HGV movements, with the exception of planned maintenance, which will be agreed with the LPAs as set out in the Operational Environmental Management Plan [**REP5-107**] which has been updated at Deadline 7. If there is unplanned

ExQ3	Respondent	Question	Applicant's Response
			maintenance at any access, i.e. as a result of unforeseen faults, HGV access would need to be agreed in advance with the LHAs, and Temporary Traffic Management measures introduced under article 44 of the draft DCO [**REP6-013**] if needed. Sunnica West Site A, Access A, at La Hogue Road will be retained from the construction phase into the operational phase. No Temporary Traffic Management is required to enable this to occur safely. The layout enables two cars to pass inbound and outbound, and an HGV and a car to pass inbound and outbound. This is suitable to ensure safe and suitable access. This is demonstrated in drawings 0017 and 0018 in Annex C of the Framework Construction Traffic Management Plan and Travel Plan [**REP5-015**]. The Applicant recognises that the aforementioned drawings did not include visibility splays. An update to these drawings has been produced to demonstrate that visibility requirements can be achieved within the Order limits. This update is appended to the Applicant's response to ExQ3, to address this question, and will be included in the next update to the Framework Construction Traffic Management Plan and Travel Plan at this Deadline 7. To clarify, this will require some vegetation clearance, but as this access will be in regular use throughout the construction, operation and decommissioning phases of the project, this is deemed necessary to ensure safe and suitable access without relying on Temporary Traffic Management through the life of the project.
Q3.10.5	The Applicant	Side agreement Regarding the emerging discussions between the Applicant and the LHAs for a side agreement in respect of inspection, certification and other highway matters, why should the agreement not be completed and submitted to the Examination before it closes?	The Applicant has been keen to progress discussions in relation to side agreements with the local highway authorities in relation to how the powers the Applicant seeks in the draft DCO would, in practice, be exercised. The Applicant provided Heads of Terms to the authorities well in advance of the start of the examination. The Applicant understands that all parties to the negotiations are keen to conclude the relevant agreements prior to the close of the examination and is working with the authorities to achieve this.
Q3.10.6	The Applicant, CCC, SCC	Side agreement What account may or should be taken by the ExA in its recommendation report in the event of any proposed party to the side agreement failing without valid reason to	The Applicant remains keen to conclude the side agreements prior to the close of the examination.

ExQ3	Respondent	Question	Applicant’s Response
		make good progress to complete the same before the close of the Examination?	In any event the Applicant has prepared a set of protective provisions which the Applicant considers appropriately protect the interests of the local highway authorities [AS-319]. The draft protective provisions provide for: - approval of detailed design of works in, or which are to form part of, the highway. - Inspection and supervision of highway works. - a power to step-in to carry out maintenance of highways in circumstances where the Applicant is liable under the terms of the DCO to maintain a highway and has failed to do so, and to recover the costs of that maintenance. - the payment of fees for the costs associated with reviewing and approving the detailed design of the highway works. - the provision of a commuted sum towards maintenance expenditure. The Applicant intends to include the draft protective provisions in the next iteration of the draft DCO. While the Applicant would prefer to reach an agreed position in relation to protective provisions and side agreements with both local highway authorities and is working towards that end; if that aim is not achieved the draft DCO would nonetheless contain the protective provisions. Irrespective of the status of the side agreements at the close of the examination, the Examining Authority will therefore be able to prepare its report and recommendation to the Secretary of State having regard to the extent by which those protective provisions address the concerns raised by the local highway authorities.
Q3.10.7	The Applicant	Costs of damage to local highway network Please provide a formula by which any eventual commuted sum to meet the costs of damage to the local highway network, due to the construction of the proposed development, may be effective and enforceable and inserted into the CTMP, or	The Applicant wishes to make a clarification. A commuted sum is a capitalised sum of money to reflect future maintenance of works. They are commonly paid to local highway authorities under the terms of Highways Act 1980 agreements where a person is carrying out works in a highway that materially increase the costs associated with maintenance. To give a hypothetical example, a developer of a housing project may be required to install a new pedestrian crossing to serve its development. The commuted sum is

ExQ3	Respondent	Question	Applicant’s Response
		provide a proposed amendment to the DCO to secure this commitment.	an agreed sum reflecting the costs associated with the maintenance of that pedestrian crossing. The highways condition surveys, set out at 7.2.15 and 7.2.16 of the Framework Construction Traffic Management Plan and Travel Plan **[REP5-015]**, will establish the pre-construction condition of the highways, providing a baseline against which subsequent condition surveys can measure to assist in identifying the extent of any damage resulting from the construction of the development. The Applicant has committed to either making good the damage itself, or providing a payment to the relevant LHA to ensure that any damaged caused to the highway as a result of the Applicant’s use of the highways to construct the project, is remediated. Until construction has been carried out, it simply is not possible to ascertain what (if any) damage has been caused as a result, nor to estimate what the costs of remediating that damage ought to be. It is therefore not possible to provide a specific cost or formula to calculate this cost. Nor is it necessary to do so because the local highway authorities have powers under section 59 of the Highways Act 1980 to recover “*extraordinary expenses*” by reason of the “*damage caused by excessive weight passing along the highway, or other extraordinary traffic thereon*”. As a consequence of these provisions it will be in the Applicant’s own interests to seek to minimise or avoid damage to the highway and, if damage does arise as a result, to appropriately remedy it.

9 Topic 3.11 - Water Resources, Flood Risk and Drainage

ExQ3	Respondent	Question	Applicant's Response
Q3.11.1	The Applicant	Sustainable Drainage Systems Will the Environmental Masterplan include the sustainable drainage features set out in the Drainage Strategy General Arrangements Drawings, Appendix F, of the Drainage Technical Note [REP5-070]? If not please explain why.	The Applicant confirms the SUDS features are included on the revised Master Plans submitted at Deadline 7.
Q3.11.2	The Applicant	Risk of flooding Will maps be included within the application documents to demonstrate the extent of pluvial flood risk, as has been provided for fluvial flood risk mapping? If not please explain why not.	Pluvial flood risk mapping has been included on the Parameter Plans; these plans have been issued as Figure 3 and Figure 4 within the revised "FRA clarification document in light of proposed Scheme changes" report [**REP5-069**], that has been re-submitted at DL6 to include the surface water mapping.

Appendices

Appendix A Supporting information for BESS (Covering Appendices A1-9)

A.1 Appendix A1 – Alternative Battery Chemistries and Diversifying Clean Energy Supply Chains

A.2 Appendix A2 – DoE Grid Storage Launchpad and DoE GSL Factsheet

A.3 Appendix A3 – EPRI BESS Fire Safety Roadmap

A.4 Appendix A4 – EPRI Lessons Learned LIB Storage Fire Prevention and Mitigation

A.5 Appendix A5 – EPRI Proactive First Responder Engagement for BESS Owners and Operators

A.6 Appendix A6 – NFCC Consultation Grid Scale BESS planning

A.7 Appendix A7 – Powin explosion prevention assessment

A.8 Appendix A8 – SAFT BESS container tests and risk analysis

A.9 Appendix A9 – ACCURE-Battery-Intelligence-White-Paper-Battery-Safety-Analytics

Atlantic Council
GLOBAL ENERGY CENTER

ISSUE BRIEF

SEPTEMBER 2022

Alternative Battery Chemistries and Diversifying Clean Energy Supply Chains

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INTRODUCTION

The energy transition from fossil fuels to low-carbon energy sources will stimulate great demand for energy storage. Batteries that can enable the clean electrification of light-duty transport and reduce the intermittency of renewable power on the grid will be a prerequisite for global decarbonization efforts. It is therefore vital that such technologies be deployed at a scale sufficient to meet the growing energy storage needs of the transition.

To date, the leading technology for those efforts has been the lithium-ion (Li-ion) battery, having displaced predecessors like lead-acid, nickel-cadmium, and nickel-metal hydride batteries because of their superior performance characteristics. Currently, Li-ion batteries account for roughly 70 percent of electric vehicle (EV) batteries and 90 percent of grid storage batteries.[1]

However, the ubiquity of lithium-ion batteries has posed obstacles to the energy transition that are likely to become more challenging as net-zero targets demand ever-more expansive energy storage solutions. Accelerating demand for lithium-ion batteries is creating a production bottleneck for energy storage as different clean technologies vie for the same mineral and metal inputs, such as lithium, graphite, nickel, and cobalt—at the same time as demand growth for such minerals and materials in other markets, such as steel-

The Global Energy Center promotes energy security by working alongside government, industry, civil society, and public stakeholders to devise pragmatic solutions to the geopolitical, sustainability, and economic challenges of the changing global energy landscape.

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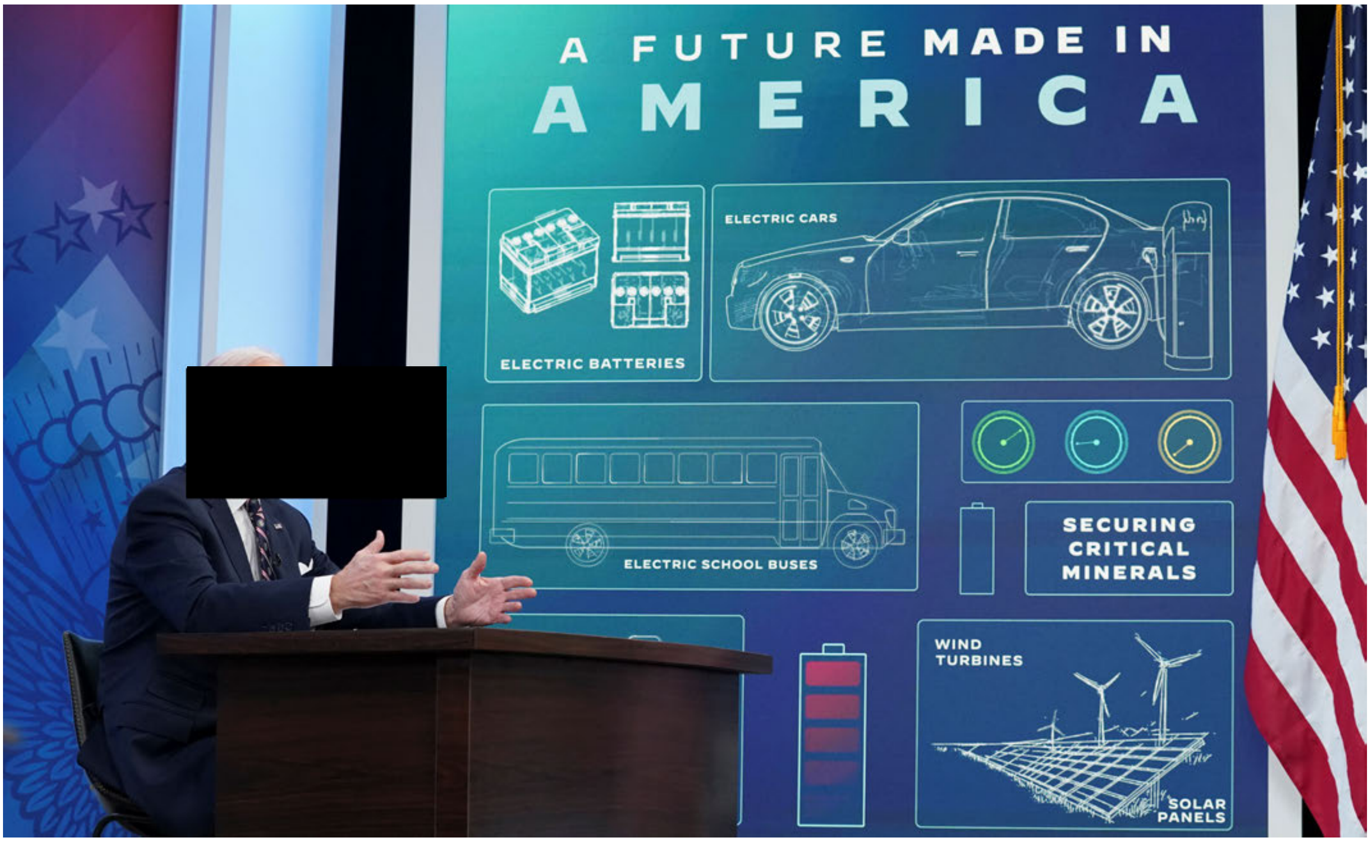
[1] Jeff Horowitz, David Coffin, and Brennan Taylor, *Supply Chain for EV Batteries: 2020 Trade and Value-added Update*, United States International Trade Commission, January, 2021, www.usitc.gov/publications/332/working_papers/supply_chain_for_ev_batteries_2020_trade_and_value-added_010721-compliant.pdf; and Alexandra Zablocki, "Fact Sheet: Energy Storage," Environmental and Energy Studies Institute, February 22, 2019, www.eesi.org/papers/view/energy-storage-2019.


[redacted]

US President Biden announced new investments in critical mineral supply chains during a virtual roundtable in February 2022. (REUTERS/Kevin Lamarque)

making, continues to grow apace amid broader economic growth. For these materials, there is currently insufficient production to meet projected demand, and existing supply chains are prone to concentration, unfair labor practices, environmental unsustainability, and increasingly, geopolitical concerns around supply-chain control. Unsurprisingly, prices for lithium-ion batteries are proving vulnerable to commodity-related volatility. For example, Russia in 2019 mined 21 percent of the world's Class 1 nickel—which is of a high enough purity to be used in EV batteries—making it the world's largest upstream producer.[2] Fears of supply shocks following Russia's invasion of Ukraine and resulting sanctions were a primary cause for massive volatility on the London Metal Exchange that lifted prices 250 percent within a day, demonstrating the risks inherent in under-developed metal markets.[3] All things being equal, these challenges run the risk of handicapping the urgent deployment of storage solutions to support net-zero targets.

Given the importance of these supply chains to decarbonization goals and economic competitiveness in the energy transition, the United States and its allies have designated many of these materials as "critical minerals," highlighting the new geopolitical pressures emerging from the energy transition. To secure a reliable supply of these minerals, Washington has recently taken novel steps to bolster security of supply at all stages of the critical mineral value chain. In March 2022, the Biden administration invoked Title III of the Defense Production Act to accelerate development of upstream and midstream infrastructure for minerals such as lithium, nickel, cobalt, graphite, and manganese.[4] Concurrently, a memorandum of understanding between the US Departments of Defense, Energy, and State proposed creating a strategic reserve for minerals critical to the energy transition through the National Defense Stockpile.[5] Furthermore, $2.91 billion has been allocated under the bipartisan infrastructure framework to support battery material refin-

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[2] Marcelo Azevedo, Nicolas Goffaux, and Ken Hoffman, "How Clean Can the Nickel Industry Become?," Commentary, McKinsey & Company, September 11, 2020, https://www.mckinsey.com/industries/metals-and-mining/our-insights/how-clean-can-the-nickel-industry-become.

[3] Jack Farchy, Alfred Cang, and Mark Burton, "The 18 Minutes of Trading Chaos that Broke the Nickel Market," Bloomberg, March 14, 2022, https://www.bloomberg.com/news/articles/2022-03-14/inside-nickel-s-short-squeeze-how-price-surges-halted-lme-trading.

[4] "Fact Sheet: President Biden's Plan to Respond to Putin's Price Hike at the Pump," White House Briefing Room, March 31, 2022, https://www.whitehouse.gov/briefing-room/statements-releases/2022/03/31/fact-sheet-president-bidens-plan-to-respond-to-putins-price-hike-at-the-pump/.

[5] "Fact Sheet: Securing a Made in America Supply Chain for Critical Minerals," White House Briefing Room, February 22, 2022, https://www.whitehouse.gov/briefing-room/statements-releases/2022/02/22/fact-sheet-securing-a-made-in-america-supply-chain-for-critical-minerals/.

ing, recycling, and battery cell manufacturing.[6] The development of processes to recycle battery materials will play an important role in strengthening critical mineral supply chains over the long term, but challenges will persist unless even more ambitious actions are taken to increase overall mineral supply to a scale commensurate with demand.

The landmark passage of the Inflation Reduction Act (IRA) of 2022 also contains a long list of relevant provisions that, at their core, are aimed at incentivizing production of energy storage technology and spurring demand for energy storage products. The IRA intends to foster new domestic manufacturing facilities for energy storage products including EV batteries; incentivize production of battery active materials, cells, and packs; and reduce the cost for producing critical minerals in the United States. The act also includes a stand-alone investment tax credit for energy storage, likely to help foster overall demand. Despite this stimulus, the growth of the energy storage sector remains threatened by limited availability of critical minerals. Resolving these supply constraints will require further effort.

Reducing the mineral intensity of energy storage by utilizing more-readily available alternatives to lithium-ion batteries could alleviate supply-chain concerns while meeting a wide array of energy storage needs—including utility-scale and distributed energy storage, which are likely to become increasingly important as a result of continued renewable energy deployment.

This paper outlines several alternative battery technologies including new lithium-ion battery designs and sodium-ion, liquid metal, sodium-sulfur, and zinc-ion batteries. It also explores the supply-chain implications of greater shares of minerals like iron, phosphate, silicon, calcium, and antimony; how these alternatives may reduce the pressure on lithium-ion supply chains, while improving the performance of an ever-widening array of energy storage contexts; and what policies can ensure that the energy transition does not become overly reliant on a single stationary storage technology. Three overarching categories are used for this analysis: battery cost and marketability, performance, and supply-chain risk. Weighing the interaction between these three categories, use cases are proposed for each novel technology, in conjunction with an assessment of their overall viability and prospects for entering development at scale as part of an "all of the above" approach for expanding a sustainable energy storage economy.

LI-ION BATTERIES, SUPPLY CONSTRAINTS, AND RISK TO THE ENERGY TRANSITION

Lithium-ion batteries have three primary advantages over their predecessors that have placed them at the forefront of the energy transition: a much higher energy density, which allows them to hold on to power for longer and to discharge a greater volume of power over a longer period of time without recharging; a relatively high and constant voltage of 3.6 volts, requiring fewer cells to work; and a lighter and more compact construction than alternative battery models, allowing producers to tailor the battery to specific uses for various range and price points.[7]

These advantages are the product of a highly efficient and adaptable chemistry. When charging, lithium in the positively charged cathode is separated from other materials as ions, which flow across a liquid electrolyte (typically lithium salt) and are stored in a negative anode (typically made of graphite). At the anode, the ions remain until discharge, a process that creates a current by sending electrons in the opposite direction.[8] Lithium is the third-lightest element in the universe, and the lightest solid element at room temperature. As an oxidizing agent, lithium is highly energy efficient and an ideal lightweight solution for anything that moves at the whole-battery level, be it portable electronics or electric vehicles. It also has a high energy density, carrying a relatively large amount of energy per unit volume compared to other materials.

Nevertheless, despite their myriad advantages over earlier battery technologies based on nickel, lead, and cadmium, raw material supply is a key challenge for the lithium-ion format—and consequently, the energy transition in general. The following mineral inputs are of particular concern.

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[6] Scooter Doll, "Biden Administration, DOE Announce $3 Billion in New Funding to Support US EV Battery Manufacturing and Recycling," Electrek, February 11, 2022, https://electrek.co/2022/02/11/biden-administration-doe-announce-3-billion-in-new-funding-to-support-us-ev-battery-manufacturing-and-recycling/.

[7] "Lithium Ion Battery Advantages and Disadvantages," Electronics Notes (website), accessed July 18, 2022, https://www.electronics-notes.com/articles/electronic_components/battery-technology/li-ion-lithium-ion-advantages-disadvantages.php.

[8] "What is a Lithium-Ion Battery and How Does it Work?," Clean Energy Institute at the University of Washington, accessed July 18, 2022, https://www.cei.washington.edu/education/science-of-solar/battery-technology/.

Batteries will be necessary to balance the intermittency of renewable energy sources, and will consume vast amounts of raw materials. (SHUTTERSTOCK)

Lithium

Given its high conductivity and light weight, the Li-ion battery's namesake mineral is incredibly difficult to substitute. According to the International Energy Agency, lithium demand will grow by a staggering forty-two times between 2020 and 2040 under a climate scenario compliant with the Paris Agreement—and even more under a 2050 net-zero scenario.[9] The lion's share of this rise in demand is expected to go toward clean energy technology—from 30 percent of the lithium demand in 2021 to 90 percent by 2040.[10] Under the Paris Agreement scenario, by 2030, global lithium supply may face a deficit of 1.75 million metric tons due to underinvestment in new production.[11]

Such a supply deficit is likely to be exacerbated by the limited number of geographies playing a role in the lithium supply chain. Lithium production is highly concentrated, with over 85 percent of production occurring in just three countries: Australia, Chile, and China.[12] While constraining current resource availability, extreme geographic concentration also presents significant risk of supply disruption, whether for political or apolitical reasons.

A crunch in available lithium supplies has already contributed to a steep rise in prices. As of January 2022, prices for lithium carbonate—a base used for lithium compounds in battery cathodes and electrolytes—rose fivefold from the year-earlier levels in China, the world's leading battery maker.[13] This price increase is significant as cathode materials are becoming an increasingly greater portion of lithium-ion manufacturing costs, from less than 5 percent of costs in 2016 to a quarter in 2021.[14] Extreme supply concentration and an illiquid market could create great instability for battery prices, presenting a severe threat to the energy transition. In 2022, demand for lithium is projected

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[9] International Energy Agency, *Mineral Requirements for Clean Energy Transitions* (Paris: IEA Publications, Revised Version, March 2022), https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/mineral-requirements-for-clean-energy-transitions.

[10] IEA, *The Role of Critical Minerals in Clean Energy Transitions, Executive Summary*, 2021, https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/executive-summary.

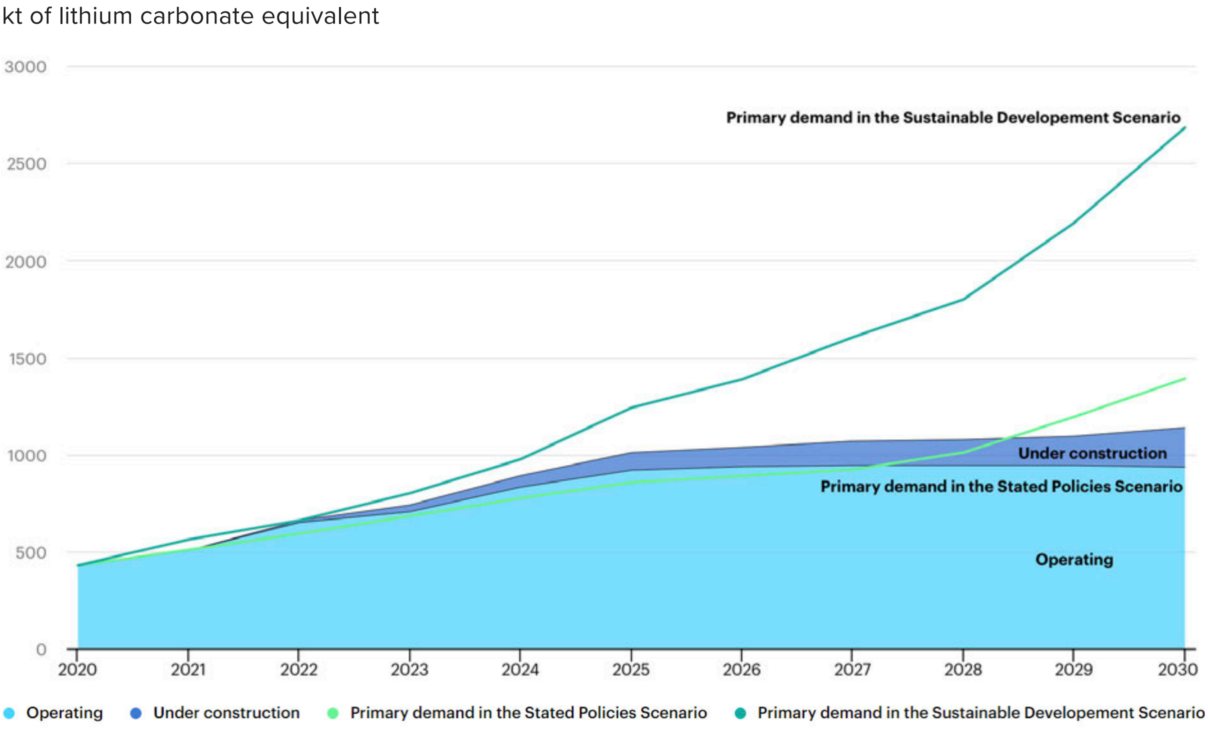
[11] "Committed Mine Production and Primary Demand for Lithium," IEA (webpage), 2021, https://www.iea.org/data-and-statistics/charts/committed-mine-production-and-primary-demand-for-lithium-2020-2030

[12] Marta Yugo and Alba Soler, "Outlook for Battery Raw Materials," *Concawe Review* 28, No. 1 (2019): 1, https://www.concawe.eu/wp-content/uploads/Battery-raw-materials-article.pdf.

[13] "EV Battery Costs Set to Rise in 2022 as Lithium Price Extends Gains," *Mining.Com*, Glacier Media Group, January 3, 2022, https://www.mining.com/ev-battery-costs-set-to-rise-in-2022/.

[14] Guiyan Zang, Jianan Zhang, Siqi Xu, and Yangchuan Xing, "Techno-economic Analysis of Cathode Material Production Using Flame Assisted Spray Pyrolysis," *Energy* 218 (2021): 119504, https://doi.org/10.1016/j.energy.2020.119504.

Figure 1: Projected lithium demand per year, measured in metric kiloton (kt) of lithium carbonate equivalent (LCE)



Source: "Committed Mine Production and Primary Demand for Lithium, 2020-2030," International Energy Agency (website), last updated May 6, 2021, https://www.iea.org/data-and-statistics/charts/committed-mine-production-and-primary-demand-for-lithium-2020-2030.

to jump to 641,000 tons, while supply is projected to reach only 636,000 tons.[15] Scant abatement of supply-chain woes are forthcoming, with market imbalances and bottlenecks caused by the COVID-19 pandemic likely to persist. Due to this stressed supply chain, lithium-ion battery pack prices recently rose for the first time since 2010, and could rise by 2 percent or more over the course of 2022.[16] This increase will impose a cost on consumers, which is rising more slowly than manufacturing and procurement costs for battery suppliers—and these costs are likely to persist due to high demand.[17] Such a scenario could represent the beginning of a significant roadblock on the way to increasing the availability of low-cost EV batteries as well as stationary storage.

It is worth noting, however, that difficulties in procuring lithium are not intractable. Despite underinvestment in extraction, lithium resources are abundant. Novel partnerships between automotive and battery manufacturers with lithium extractors to leverage vertical integration are bringing new lithium supply to market quickly and at scale. As these alternative sources of lithium come online, the metal will continue to be a pillar of electrical storage solutions to power the energy transition. But there remains a potential for supply and demand mismatch if the scaling of lithium ion-based battery storage outpaces the ability of new supply to come online, given the long lead times that bedevil the international mining industry. Alternatives that can find niche uses alongside lithium, therefore, can prove invaluable for lightening the herculean task that awaits the lithium industry amid the global race to net zero.

Graphite

Supply concerns for graphite, the key ingredient for the lithium-ion anode, are far more acute than for lithium. The United States currently does not produce any natural graphite and is wholly reliant on imports, with 33 percent of its graphite being sourced from China alone between 2015 and 2018. With only 4 percent of the world's total graphite reserves being found within North America, the United States will not be able to achieve self-sufficiency in the production of graphite and is likely to encounter geopolitical risk in sourcing graphite for the foreseeable

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[15] Jacqueline Holman and Henrique Ribeiro, "Commodities 2020: Global Lithium Market to Remain Tight," S&P Global Commodity Insights, December 14, 2021, https://www.spglobal.com/platts/en/market-insights/latest-news/energy-transition/121421-commodities-2022-global-lithium-market-to-remain-tight-into-2022.

[16] Rurika Imahashi, "Battery Costs Rise as Lithium Demand Outstrips Supply," *Financial Times*, January 11, 2022, www.ft.com/content/31870961-dee4-4b79-8dca-47e78d29b420.

[17] Robert Rapier, "The Challenges Posed by Rising Lithium Prices," *Forbes*, December 31, 2021, www.forbes.com/sites/rrapier/2021/12/31/the-challenges-posed-by-rising-lithium-prices/?sh=9d509083af90.

future.[18] Graphite shortages are projected to be significant in 2022, as the 93 percent of global midstream production that occurs in China has been disrupted by the severe, pandemic-related lockdowns.[19] Benchmark Mineral Intelligence forecasts a 20,000 metric ton shortage of graphite—about what is needed to produce a quarter-million electric vehicle batteries.[20]

Cathode Components

The picture for cathodes is more complex. While all cathodes need lithium, the cathode is stabilized by a number of other metals in various combinations. There are four main types of lithium-ion cathode options on the market today: nickel-manganese-cobalt oxide (NMC), which accounts for 70 percent of the lithium-ion market,[21] nickel-cobalt-aluminum (NCA), lithium-iron-phosphate (LFP), and lithium-cobalt oxide (LCO).

Cobalt plays a significant role across nearly all of these cathodes. The metal improves battery safety by increasing thermal stability and increases energy density to add to lithium-ion batteries' lifespan and capacity. These benefits, however, come at the expense of political risks as well as environmental, social, and governance (ESG) reputational risks. Two-thirds of global cobalt production occurs in the Democratic Republic of the Congo (DRC), a country that has historically been susceptible to poor resource governance and the practice of artisanal mining, known for unsafe conditions and the use of child labor. Moreover, Chinese investors control 70 percent of the DRC's mining sector and China itself refines 80 percent of global cobalt supply, making the metal a significant source of political risk as the geopolitical tensions of the energy transition unfold.[22]

Increasing cobalt supply also is a challenge. Cobalt is retrieved as a by-product of copper and nickel mining, contributing to low levels of liquidity and making its retrieval uneconomical if prices are not sufficiently high. As economies of scale develop in already-concentrated cobalt supply chains, the prospect of adding alternative sources of supply will face high barriers to entry and little chance of cost-competitiveness.[23]

Nickel is another challenge for lithium-ion cathodes, with Tesla CEO Elon Musk calling the metal the "biggest concern" for EV batteries in February 2021.[24] Most nickel production is concentrated in three countries—Indonesia, Philippines, and Russia—and unlike cobalt and lithium, energy storage-related demand for nickel is competing against a broad array of other uses, including other clean energy technologies.[25] By 2024, Rystad Energy predicts, the supply of battery-grade nickel will fall short of demand.[26]

Also of note is manganese, another critical mineral as listed by the US Geological Survey. Manganese, like nickel, is a metal where batteries are an afterthought within primary demand: manganese's principal use is in steelmaking, accounting for roughly 90 percent of total manganese demand.[27] China is dominant in manganese as well, controlling 93 percent of global refining.[28] Power shortages in China at the end of 2021, however, disrupted that supply chain, leaving European manganese users facing an acute supply crunch.[29]

In sum, despite the triumph of lithium-ion batteries in the electricity storage market, the mineral components of the Li-ion battery are at significant risk of undersupply, disruption, and geopolitical gamesmanship. Left unchecked, these risks may manifest themselves in the form of component shortages and high prices, limiting efforts to deploy energy storage solutions to improve renewable energy intermittency and ensure wide availability of low-cost electrified transport options.

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Reducing Mineral Intensity in the Lithium-ion Supply Chain

Optimizing existing and deployed technologies in line with supply chain realities can offer the path of least resistance to reduce the critical mineral intensity of lithium-ion batteries. The most pressing agenda item for the battery industry will be reducing the intensity of particularly problematic minerals, chiefly cobalt and graphite.

New cathode materials have the potential to resolve industry's most conspicuous supply chain governance and resilience challenge. Reductions in cobalt intensity for the dominant lithium-ion cathode, nickel-magnesium-cobalt (NMC), are being deployed now. For example, LG's NMC 811 is a cathode material containing eight parts nickel and one part each of cobalt and magnesium. In contrast, other NMCs contain equal parts of the three metals or three parts nickel and one part each of cobalt and magnesium. NMC 811 is being used in General Motor's new Hummer EV and Tesla's Chinese Model 3. Ultium Cells, a joint venture of LG Energy Solutions and GM, makes a battery used in GM's other EVs that reduces the need for both cobalt and magnesium—another critical mineral—in the cathode even further, with seventeen parts nickel for one part each of cobalt, magnesium, and aluminum, reducing cobalt and magnesium by 70 percent.[30] Cobalt-free batteries, such as LFP (lithium-iron-phosphate) batteries, also offer a less mineral-intense version of a lithium-ion configuration and often are less expensive than their NMC counterparts, though at the cost of reduced energy density and therefore storage capacity concerns such as EV driving range.

The impetus to "engineer away" nickel and cobalt from the electric vehicle battery supply chain has been gaining momentum. In August 2022, UBS and BloombergNEF predicted that the LFP chemistry would comprise 40 percent of the global battery market by 2030—for UBS, this represented a 25 percent increase over previous forecasts.[31] LFP batteries held only a 17 percent global market share in 2020.[32] LFP cathodes have long enjoyed subsidies in China as part of a state-driven push for vertical integration. Consequently, LFP has become the flagship chemistry for CATL and BYD, the world's largest and fifth-largest electric vehicle battery manufacturers.[33]

Alternative anodes, meanwhile, can alleviate dependence on graphite, the primary material used for the negative electrode in lithium-ion batteries. Silicon in particular has shown great promise at the testing stage. Tesla has been experimenting with increasing the use of silicon in its anodes both for its long-range NMCA and its short-range LFP batteries through a cathode-agnostic silicon-graphite blend.[34] There is room to reduce graphite, lower costs, and boost energy density by mixing silicon with graphite or carbon. An all-silicon anode is a possibility as well, although a fully stable, silicon-based anode has as yet proven elusive because of materials science challenges.[35] Silicon anodes are also cathode agnostic, allowing them to be deployed with either NMC or LFP cathodes; testing by Tesla has demonstrated that the energy density of the anode can be increased while significantly reducing anode costs by a factor of six to ten. This reduction can lower overall lithium-ion costs per kilowatt-hour by 77 percent if paired with a conversion-based cathode, rather than intercalation-based ones that currently predominate the market.[36]

EVALUATING ALTERNATIVES TO LITHIUM-ION

So long as electrification, the energy transition, and other battery markets continue to propel demand for energy storage, new technologies that can ease the pressures placed upon the associated materials supply chains can offer immeasurable value. This need is especially true as the range of use cases where energy storage will be required expands in a rapidly electrifying energy system—and the size, weight, or energy density advantages of lithium-ion technologies for electric vehicle batteries become less critical in diverse energy-storage use cases. The growing range of use cases presents an opportunity to explore where new technological solutions can sufficiently diversify or reduce mineral inputs to lessen supply risks. In doing so, battery innovations may also improve performance, cost, or safety relative to the prevailing Li-ion batteries on the market. Key indicators include:

- **Performance**: How does a Li-ion alternative offer added value to the performance capabilities of a status quo technology, either in terms of output (capacity or energy density) or function (flexibility or product compatibility)? How do these alternatives impact product safety?

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- **Price and competitiveness**: How do the material components of the alternative battery technologies and corresponding manufacturing costs compare to current Li-ion batteries, particularly in light of the economies of scale and cost reductions that have developed across the Li-ion supply chain?

- **Supply security**: Do the material components of the alternative battery designs alleviate concerns around current (or projected) material availability?

The following sections explore several representative potential use cases for alternative batteries, with particular attention to their merit relative to the aforementioned factors.

Option 1: Sodium-ion Chemistries

A sodium-ion battery works similarly to the standard lithium-ion battery; the former type, however, circulates sodium atoms rather than lithium. During discharge, sodium ions travel from a carbon-based anode across the aqueous sodium-based electrolyte to be stored in the cathode. The principal difference is the size of the ion; while sodium atoms are bigger and heavier than lithium atoms, sodium is still lighter than nearly every other metal. Nevertheless, sodium-ion batteries may still be viable for use in heavier electric vehicles, representing an even more budget-friendly alternative to LFP lithium-ion batteries by reducing costs while minimizing an increase in weight and diminution in energy density.[37]

- **Performance**: Sodium-ion batteries offer greater longevity than lithium-based counterparts, with models featuring a life cycle of fifteen years in development or early production, in comparison to lithium-ion's standard ten-year average life cycle.[38] That being said, on performance, sodium-ion batteries are a marked downgrade from lithium-ion, with lower energy density and longer charging times. Since a fully sodium-ion battery may need as much as twice the volume to achieve the same energy density of a lithium-ion NMC battery, the adoption of a pure sodium-ion chemistry—with no lithium-ion hybridization—as an EV battery may be somewhat limited.[39] Meanwhile, sodium-ion batteries offer several safety benefits compared to lithium-ion-only batteries, as they can operate in a wider range of temperatures without incurring thermal runaway, boding well for home and grid-scale uses where weight is less of an issue.

- **Price and competitiveness**: Sodium is highly plentiful and raw materials consequently make up a much smaller proportion of manufacturing costs for sodium-ion batteries. In fact, it is estimated that if the prices of all the metals used to make the sodium-ion cell increased by 10 percent, overall sodium-ion production costs would consequently increase by less than 1 percent, in comparison with a 3.2 percent rise in LFP costs and a 4.6 percent rise in NMC costs.[40] Chinese media have claimed that first-generation battery pack costs will approach $77 per kilowatt-hour, with economies of scale contributing to costs reaching $50 per kilowatt-hour in the near future.[41] This cost compares to an average lithium-ion battery pack cost of $132/kWh in late 2021, with pack costs of below $100/kWh not foreseen until at least 2024, according to Bloomberg New Energy Finance (NEF).[42]

- **Supply security**: Similar to an LFP lithium-ion battery, sodium-ion batteries offer lower energy density than NMC batteries, in exchange for the absence of cobalt or nickel components, alleviating supply chain risks. Sodium-ion batteries also are incompatible with graphite anodes, which cannot store the larger sodium ions. These batteries therefore use carbon-based anodes instead. Research efforts have enabled previously favored metal-oxide cathodes to be forgone in favor of polyanion cathodes, which increase security of supply. For instance, sodium-ion cells can be manufactured with a cathode consisting of a material called Fennac (aka "Prussian white"), composed of sodium, iron, carbon, and nitrogen, none of which are critical minerals.[43] This chemical makeup therefore limits supply risk substantially.

With greater resilience against potential fluctuations in metal prices, sodium-ion technologies have potential as a swing battery format in times of high lithium-ion resources costs. Cost considerations aside, the performance limitations of sodium-ion batteries—particularly relating to energy density—mean the format should be understood as primarily an even lower-end substitute for LFP batteries, and not necessarily as a practical alternative to high-performance Li-ion chemistries. This limitation does not, however, pre-

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37 "CATL Unveils Its Latest Breakthrough Technology by Releasing Its First Generation of Sodium-ion Batteries," Contemporary Amperex Technology Co. Ltd. (CATL), July 29, 2021, https://www.catl.com/en/news/665.html.

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42 "Battery Pack Prices Fall to an Average of $132/kWh, but Rising Commodity Prices Start to Bite," BloombergNEF, November 30, 2021, https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/.

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clude sodium-ion from offering value in contexts where that density is not a prerequisite, such as home or grid storage, where the safety advantages of a sodium-ion or sodium-ion mix would be of paramount importance.

Option 2: Liquid Metal Batteries

Liquid metal batteries—also referred to as molten salt batteries—operate uniquely compared with their lithium-ion and sodium-ion counterparts. The chemistry combines an anode of liquid calcium alloy, a molten salt electrolyte, and a cathode of solid antimony. When the battery discharges, the lighter calcium alloy anode, which is also in a molten state, releases electrons that flow through the electrical circuit to provide power, and calcium ions that flow through the molten salt electrolyte and form an alloy at the solid antimony cathode. During the charging cycle, the calcium-antimony alloy disassociates and the calcium ions flow back through the electrolyte. Ambri, a Massachusetts company that has pioneered the format, settled on antimony as the cathode and a liquid calcium alloy as the anode, having originally tried magnesium.[44] Ambri believes the battery combines the elements of a low-cost, long-lasting chemistry using commonly available materials with little supply constraints.

- **Performance**: The liquid metal battery uses much heavier components than lithium- or even sodium-ion batteries, particularly given the presence of antimony. As such, liquid metal batteries are far too heavy for practical use in EVs and portable electronics, but they could offer highly cost-effective stationary energy storage for the grid. Compared to a battery with a lithium anode, which is highly reactive, a calcium-antimony battery offers greater stability, a longer lifespan, and less need for external temperature regulation.[45] The greater weight of the liquid metal battery precludes its use for EVs; however, for stationary storage, the battery's response time of less than a second and its twenty-year lifetime with minimal degradation could make the type a major player in grid-scale applications.[46]

- **Price and competitiveness**: The liquid calcium electrode and calcium-chloride salt electrolyte proposed by Ambri consist of metals which are highly abundant and affordable. At a price of about $13,000 per metric ton as of February 2022, antimony is roughly equal in price to nickel and about 40 percent and 80 percent cheaper than lithium and cobalt, respectively.[47] Ambri estimates cost savings of 25 percent to 50 percent versus lithium-ion by 2025, even accounting for projected decreases in lithium-ion costs.[48] The newer technology may presently require higher initial capital investment associated with market entry and building economies of scale. In the long-term, however, the company forecasts that input costs will be lower than prevailing lithium-ion technologies once brought to scale. Moreover, the lack of a need for temperature regulation and fire suppression for the highly stable battery should lower the life-cycle cost of storage when economies of scale can be achieved.

- **Supply security**: With half of the battery's estimated cell weight composed of calcium and stainless steel, both of which offer very low supply risk, the primary supply risk for the battery is associated with the use of antimony, which is used primarily in military technologies. Some 83 percent of the world's production originates in China.[49] However, only 32 percent of the world's proven reserves are found in China, with significant reserves in Turkey, Bolivia, Australia, and the United States.[50] Ambri has sought to mitigate this imbalance in the short term through an antimony production agreement with Perpetua Resources, with its mine set for a 2027 opening date in Idaho.[51] As the technology is scaled up, alternative supplies may also need to be brought online.

Liquid-metal battery solutions such Ambri's exemplify the benefits of a "big tent" approach to energy storage. While the relatively higher weight of a liquid metal, antimony-based battery for a given capacity would be a disadvantage for a consumer EV, it would offer stability and performance improvements for other storage applications where weight is not a significant factor such as utility-scale grid storage solutions. These characteristics offer the additional advantage of disconnecting critical pieces of an electrified grid from a highly competitive, lithium-ion supply chain, at substantial net-cost benefit. While a liquid-metal configuration would replace supply concerns related to lithium, cobalt, and nickel with possible supply risk from antimony, the latter metal presents a more resilient supply chain given its relative abundance and more limited demand projection.

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Option 3: Zinc-ion Batteries

Zinc-ion batteries function analogously to the previously described lithium- and sodium-ion technologies, but with a zinc anode that discharges its ions across a water-based electrolyte to be stored in a zinc-based cathode. Zinc is heavy, but lower input costs may allow zinc-ion technology to provide another low-cost option for stationary power storage. Two start-ups are already fulfilling contracts for zinc-ion-based storage in the United States: Eos Energy, which is providing grid-scale storage for the states of California and Texas and for North Carolina-based solar provider Blue Ridge Power;[52] and Salient Energy, which has received $1.5 million from the California Energy Commission to make home-scale batteries in the state.[53]

- **Performance**: In addition to its safety advantages over lithium-ion batteries, zinc-ion batteries can last fifteen to twenty years, with little degradation over that long lifespan. However, they have significantly lower efficiency, at 65 percent, compared with the 90 percent to 100 percent efficiency of liquid metal and lithium-ion batteries.[54]

- **Price and competitiveness**: Zinc is considerably cheaper than lithium-ion materials, at a projected average of roughly $2,800 per metric ton—12.5 percent the cash price for an equivalent amount of nickel in February 2022—lowering the upfront capital costs for battery production.[55] Unlike lithium, zinc is not reactive with water, enabling zinc-ion to use water as a cheap electrolyte and eliminating the need for a costly, hyper-controlled manufacturing environment. The water-based electrolyte also eliminates the risk of fire, increasing safety and precluding the need for costly features to prevent overheating, and there is no need for formation cycling at the end of the manufacturing process, allowing for a quicker rollout to consumers. In fact, it is projected that the levelized cost of storage will reach two-thirds that of lithium-ion, and the battery format also offers the potential for a longer lifespan than lithium-ion.

- **Supply security**: Although zinc has recently been classified as a critical mineral by the US Geological Survey, the supply risks for this commonly used element are less acute than for other battery materials. The zinc supply chain is relatively diversified, with one-third of global production coming from the United States, India, Peru, and Australia.[56] These countries combined account for half of the known global reserves, suggesting a relatively light level of political risk if overall supply can be brought to market at a scale commensurate with demand.[57] Moreover, due to their material composition, the batteries have better prospects for end-of-life recycling.[58] Zinc-ion batteries typically use a zinc metal anode and an aqueous electrolyte. This design has been prototyped with a variety of cathode materials such as manganese-based oxides, vanadium-based materials, and "Prussian blue" (a ferrous cyanide powder). However, manganese oxide is emerging as a favored variant.[59] As previously mentioned, however, manganese is a critical mineral given its importance to steelmaking, suggesting that absent additional sourcing, a shortage of battery-grade quality manganese could develop.[60]

In summary, zinc-ion batteries may offer a practical alternative to lithium-ion batteries in use cases where the energy density or efficiency may be a less critical performance requirement. This is particularly true given the possible cost benefits of a zinc-ion technology and the potential cost-resiliency against material supply availability. Zinc-ion batteries, therefore, may be of considerable use as a low-cost option for private stationary storage or as an intermittency solution for smaller-scale, renewable energy production.

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[54] Leigh Collins, "Zinc-ion Batteries: 'Up to 50 Percent Cheaper than Lithium-ion with No Raw Materials Concern,' " *Recharge News*, January 11, 2021, https://www.rechargenews.com/transition/zinc-ion-batteries-up-to-50-cheaper-than-lithium-ion-with-no-raw-materials-concerns/2-1-939768.

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[56] "Zinc Facts," Government of Canada, February 3, 2022, https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/minerals-metals-facts/zinc-facts/20534.

[57] Amy Tolcin, "Zinc," US Geological Survey, January 2022, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-zinc.pdf.

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[60] "Manganese Joins the List of 23 Elements Critical to the US Economy," Cision PR Newswire, February 2, 2018, https://www.prnewswire.com/news-releases/manganese-joins-the-list-of-23-elements-critical-to-the-us-economy-672335963.html.

Option 4: Sodium-sulfur Batteries

Sodium-sulfur batteries consist of a molten sulfur cathode and a solid ceramic electrolyte consisting of beta-alumina, which despite its name, is made largely from sodium. The construction of the battery is simple, with an outer casing of sulfur that constitutes the cathode, and an inner container that stores the sodium, separated by the beta-alumina solid electrolyte (BASE).

- **Performance**: As a grid-scale energy storage system, sodium-sulfur batteries pack significant power. They boast an 85 percent efficiency rate, a quick response time, a fifteen-year lifespan, and even have a higher theoretical energy density of 760 watt-hours per kilogram, versus 570 watt-hours per kilogram in lithium-ion.[61] Existing sodium-sulfur technology already has achieved an energy density of 110 watt-hours per kilogram, which competes with the lithium-ion incumbent's density of 100 to 265 watt-hours per kilogram.[62] The main drawback of sodium-sulfur batteries is that they require high operating temperatures, although novel electrolyte mixtures offer the potential for room-temperature use.[63]

- **Price and competitiveness**: The need to maintain a high operating temperature for sodium-sulfur batteries is the biggest current impediment to price competitiveness. The batteries cost as much as $500 per kilowatt-hour as of 2019, but the Institute of Electrical and Electronics Engineers predicts the cost will fall 75 percent by 2030.[64] The simplicity of the battery's design and the low price of inputs should contribute to cost competitiveness once the operating temperature issue has been resolved.

- **Supply security**: Salt and sulfur are both highly abundant and the United States is a leading global producer of both minerals, with a net import reliance in 2020 of 29 percent and 7 percent, respectively.[65] The anode, typically made of steel, chromium, and molybdenum, is also relatively low risk, although molybdenum is classified as a critical mineral, alongside aluminum.[66]

Sodium-sulfur offers another variable cost solution that has a history of large-scale grid storage deployment. The plentifulness of both liquid sodium and sulfur as cathode and electrolyte, combined with the ability for sodium-sulfur batteries to utilize a chromium and molybdenum-derived casing as an anode, also reduces the complexity of manufacturing. While performance at cost remains dependent on the ability to sustain operation at a reasonable temperature, which currently limits wider commercial deployment capacity, sodium-sulfur batteries have the potential to achieve cost competitiveness with lithium-ion for certain technological innovations.

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[62] Ahmet Aktaş and Yağmur Kirçiçek, "Solar Hybrid Storage and Energy Systems," in *Solar Hybrid Systems* (Cambridge, Massachusetts: Academic Press, 2021), 87-125, https://doi.org/10.1016/B978-0-323-88499-0.00005-7.

[63] Xiaofu Xu et al., "A Room Temperature Sodium-sulfur Battery."

[64] Mads Almassalkhi, Jeff Frolik, and Paul Hines, "How to Prevent Blackouts by Packetizing the Power Grid," *IEEE Spectrum*, Institute of Electrical and Electronics Engineers, January 29, 2022, https://spectrum.ieee.org/packetized-power-grid#toggle-gdpr.

[65] Wallace Bolen, "Salt," US Geological Survey, January 2020, https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-salt.pdf; and Lori Apodaca, "Sulfur," US Geological Survey, January 2020, https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-sulfur.pdf.

[66] Paul Breeze, "Power System Energy Storage Technologies," in *Power Generation Technologies*, Third Edition (Oxford and Boston: Newnes, 2019), 219-249, https://doi.org/10.1016/C2017-0-03267-6.

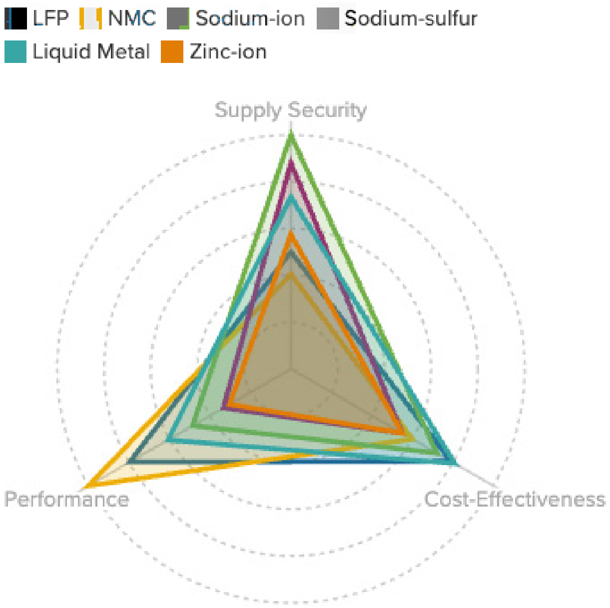
Figure 2: The Battery Trilemma: Supply Security, Performance, and Cost

The Atlantic Council Global Energy Center (GEC) devised a set of scored values meant to represent the characteristics of each battery chemistry in terms of its supply security, cost-effectiveness, and performance. The values assigned to each battery are positive and are meant to be interpreted in relation to each other. The methodology by which the values were assigned is described below:

Supply Security: To represent the degree to which each battery's supply chain has been assessed to be secure, these values have been assessed by referencing the US Geological Survey's Methodology and Technical Input for the 2021 Review and Revision of the US Critical Minerals List. Per GEC analysis, projections regarding future production or geopolitical trends have also informed the final index values.

Cost-Effectiveness: To represent the relative affordability for each battery chemistry, values were assigned via a comparison of battery pack cost per kilowatt-hour across each chemistry.

Performance: To compare performance among battery chemistries, the GEC has elected to reference gravimetric energy density values as the basis for assigning values for performance. While other metrics, such as C-rate, are relevant to assessing a battery's performance, the GEC has elected to focus on energy density for consistency and for its centrality for determining power or cycle duration.




LFP

NMC

Sodium-ion

Sodium-sulfur

Liquid Metal

Zinc-ion

Source: US Geological Survey, BloombergNEF, Institute of Electrical and Electronics Engineers, American Chemical Society, CleanTechnica, PRNewsWire, National Center for Biotechnology Information, and MDPI.

DIVERSIFYING CLEAN ENERGY SUPPLY CHAINS THROUGH ALTERNATIVE BATTERY CHEMISTRIES

As demand for a wide array of energy storage solutions continues to grow as a result of electrification throughout the energy system, battery storage will add to a range of clean energy technologies currently competing for critical raw materials. The corresponding strain on clean energy technology supply chains—from mines to finished goods—is of growing concern as the supply of key raw materials tightens, technologies become more expensive, and concerns around supply-chain resiliency emerge, prompting national governments to prioritize the sustainability of such supply chains in terms of environmental stewardship, good governance, and transparency. Such considerations are only growing in relevance, following politically motivated disruptions caused by the 2011 Chinese embargo of rare earth exports to Japan, more recent concerns around nickel supply following Russia's invasion of Ukraine, continued worries surrounding the sustainability of cobalt mining and rare earth processing in the DRC and China, respectively, and current increases in overall lithium-ion battery costs due to tightening lithium markets. Amid Russia's explicit weaponization of natural gas, for which it provides 40 percent of the European Union's total supply, the necessity for diversifying sources for essential commodities has become increasingly apparent.[67] A forward-thinking approach to economic and energy security, as the transition to net-zero emissions continues, will center the diversification of mineral inputs as a vital national interest.

Demand for batteries as an energy storage solution will impose particularly acute pressures on these supply chains, given the significant share of overall mineral demand that battery storage is expected to establish over the course of the energy transition. Battery metal supply chains are heavily concentrated, not only in terms of geography, but in the small handful of minerals which are essential to battery deployment; namely, cobalt, graphite, lithium, and nickel.

It stands to reason, therefore, that the variety of solutions for battery storage should be examined not only as a means by which to more efficiently achieve energy storage goals—through performance and cost-effectiveness and for an increasingly wide range of storage applications—but also as an opportunity to alleviate concerns around mineral pricing, accessibility, and sustainability.

Diversification of Mineral Inputs

Chief among the benefits of diversifying battery technologies is the associated diversification of mineral inputs throughout battery supply chains. By utilizing other minerals for certain flexible use cases, alternative battery materials may ease the pressure on fragile and underdeveloped supply chains, allowing the energy storage industry to avoid input disruption and cost volatility that could impede the marketability of energy storage.

The battery alternatives discussed above offer pathways to such diversification by widening the aperture of minerals and materials that can form an effective energy storage chemistry and, in doing so, also diversify the available avenues of production for said minerals—both in terms of resource potential and producing geographies. Examples include:

- Iron and phosphate, the basis of the LFP cathode, which are both highly abundant. For iron, prices have been stable in the low $90s per ton over the past four years, and the United States is a net exporter of the metal.[68] For phosphate rock, the United States is the world's leading producer and a small net importer, with nearly 90 percent of the imports from fellow Energy Resource Governance Initiative (ERGI) member Peru.[69]

- Silicon, as a potential alternative to graphite in the anode, is also not a critical mineral.[70] It is easily extracted from sand and the composition of the earth's crust is roughly 15 percent silicon by mass.[71] Noncobalt cathodes and nongraphite anodes, therefore, can play an even greater role in the diversification of the supply chain.

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[67] "In Focus: Reducing the EU's Dependence on Imported Fossil Fuels," European Commission, April 20, 2022, https://ec.europa.eu/info/news/focus-reducing-eus-dependence-imported-fossil-fuels-2022-apr-20_en#:~:text=REPower%20EU%20to%20cut%20dependence,and%20cost%20%E2%82%AC99%20billion.

[68] Cris Tuck, "Iron Ore," US Geological Survey, January 2022, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-iron-ore.pdf.

[69] Stephen Jasinski, "Phosphate Rock," US Geological Survey, January 2022, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-phosphate.pdf. The ERGI, which focuses on best practices in the mining sector, was founded by Australia, Botswana, Canada, Peru, and the United States; see "About ERGI," https://ergi.tools/about.

[70] "2022 Final List of Critical Minerals," 87 Fed. Reg. 10,381, February 24, 2022, https://www.govinfo.gov/content/pkg/FR-2022-02-24/pdf/2022-04027.pdf.

[71] "Silicon," Institute for Rare Earths and Metals (website), accessed July 18, 2022, https://en.institut-seltene-erden.de/seltene-erden-und-metalle/strategische-metalle-2/silizium/.

Alternative Battery Material(s)	Usage	Supply
Iron and phosphate	Basis of the LFP cathode	Most iron and phosphate used by US companies come from the United States and Peru.
Silicon	Potential alternative to graphite anodes	Silicon is easily extracted from sand without geographic limitations.
Sodium	Forms the core of alternatives to lithium-ion batteries	Sodium-based materials can be produced via the electrolysis of abundant sodium-containing salts.
Calcium	Key ingredient (negative electrode) of the molten salt battery	Calcium is sourced from abundant lime (calcium oxide and calcium hydroxide) and crushed stone (calcium carbonate).
Sulfur	Used as positive electrode in the sodium-sulfur battery	Sulfur is a waste product, and is stockpiled by fossil fuel-producing countries, including Canada.
Antimony	Cathode material in liquid-metal batteries	The first US-based antimony mine is scheduled to begin operations in 2027.

- Sodium-based materials that form the core of alternatives to lithium-ion batteries, while not abundant in nature, can be produced by the electrolysis of salt, which is highly abundant in seawater, salt mines, and other resources. The US Geological Survey notes that the world's salt reserves, when including both ground deposits and oceanic salt, are "virtually inexhaustible."[72]

- Calcium, a key ingredient of the molten salt battery, is the fifth-most abundant element in the earth's crust.[73] It is extracted as lime (calcium oxide and hydroxide) and as crushed stone (calcium carbonate), both of which are plentiful enough for the USGS to decline to quantify their reserves.[74]

- Sulfur, used in combination with sodium in the sodium-sulfur battery, is a waste product and in surplus, stockpiled by fossil fuel producers like Canada, which produces sulfur at a high rate from tar sand oil production, at one point reaching a total stockpile of 12 million metric tons in 2006.[75]

- Antimony, the cathode material in Ambri's liquid-metal battery, is a critical mineral for which no mining activity was reported in the United States in 2021.[76] However, Perpetua Resources—which is presently developing an antimony mine in Idaho, which it aims to bring into operation by 2027—has secured supply agreements with Ambri, promising the creation of a localized antimony battery supply chain in the United States.

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[72] Wallace Bolen, "Salt," US Geological Survey, January 2020, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-salt.pdf.

[73] "Calcium," Royal Society of Chemistry, 2022, https://www.rsc.org/periodic-table/element/20/calcium.

[74] Lori Apodaca, "Lime," US Geological Survey, 2021, https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-lime.pdf; and Jason Willett, "Stone Crushed," US Geological Survey, 2022, https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-stone-crushed.pdf.

[75] G. D'Aquin, "Sulfur Output from Oil Sands: Dramatically Changing Alberta's Sulfur Balance," *Proceedings of the 2 Oil Sands Heavy Oil Technologies Conference* (Tulsa, Oklahoma: PenWell, 2008), 1000, summary available at International Nuclear Information System (INIS) 40, no. 13, reference 40030986, International Atomic Energy Agency, https://inis.iaea.org/search/search.aspx?orig_q=RN:40030986.

[76] Klochko, "Antimony."

Supporting Sustainable Clean Energy Supply Chains

Meanwhile, broadening the range of mineral inputs for chemical battery storage will open new opportunities to support the development of clean energy supply chains which meet the criteria increasingly mandated by clean energy stakeholders: environmental sustainability, good governance, and market transparency. Taking advantage of such opportunities will be critical to maintaining the overall health of clean energy supply chains as demands on mineral inputs increase incentives for marginal, and frequently less sustainable, producers as more mainstream battery materials slowly come online.

An immediate opportunity to improve the sustainability of clean energy value chains will be the expansion of battery material inputs to a range of materials that require less environmentally intensive production processes. Much of this benefit can be achieved courtesy of the wide availability of alternative battery metals such as salt, sulfur, silicon, or calcium—which are not only less of a sustainability concern than traditional battery materials such as cobalt, but also can be more readily integrated into the battery supply chain through their retrieval as by-products from existing mining activity, thereby mitigating land use concerns.

A corollary to the sustainability benefits of a wider array of mineral inputs into the battery supply chain is the expansion of potential sourcing of battery minerals from partners with stronger mechanisms for market governance and greater sustainability credentials. Here, the easy integration of best-in-class mining industries in the United States, Canada, Australia, and others will improve supplies of sustainably mined minerals—not necessarily on a cost-cost comparison with existing mineral supply chains, but by offering alternative markets in which those supply chains can develop.

Finally, a key sustainability benefit of a "big-tent" approach to alternative battery technologies will be the reduction of mineral intensity. This benefit includes an overall reduction of demands on specific minerals throughout the clean energy supply chain—through similar chemistries with different concentrations of key minerals—but also offering stronger opportunities for batteries with low mineral intensities to be brought to market and deployed at scale. Much of this work is already in progress, with reductions to the cobalt intensity of NMC lithium-ion batteries already gaining traction in the EV industry. Seizing this momentum to other storage contexts will add significant value by improving the overall health of the clean energy supply chain.

AREAS FOR ACTION

Securing the necessary mineral inputs to drive the energy transition will require action on the part of government to steer the market toward a greater diversity of mineral inputs. Such action is already happening; for instance, in July 2022, the US Department of Energy (DOE) Loan Programs Office lent $102 million to support Syrah Technologies' Vidalia project for processing graphite in Louisiana, sourced from mines in Mozambique owned by its Australia-based parent company, Syrah Resources, thereby creating a US-controlled, end-to-end supply chain in a mineral for which the United States is currently wholly reliant on China-based processors.[77] Previously, in January 2021, DOE's Advanced Manufacturing Office unveiled a series of fifteen critical minerals projects slated to receive funds totaling $50 million.[78]

However, US public financing in this market has largely centered on fixing the supply chain bottlenecks associated with lithium-ion batteries. In terms of enabling technologies which use diversified and abundant inputs, the European Union has announced funding for developing stable sodium-ion batteries, a complementary effort to the United States' National Science Foundation partnership with Brussels via a consortium of academic institutions.[79] It remains clear that in addition to supporting lithium-ion supply chains, policymakers must redouble their efforts to invest in an array of material inputs which support a portfolio of diversified battery technologies for tailored use profiles.

For policymakers to further these efforts, actions will produce benefits most efficiently by targeting the following areas of focus:

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[77] Jeff St. John, "DOE Backs US Battery Materials Production with $107 Million Loan," *Canary Media*, April 18, 2022, https://www.canarymedia.com/articles/batteries/doe-backs-us-battery-materials-production-with-107m-loan#:~:text=DOE%20backs%20US%20battery%20materials%20production%20with%20%24107M%20loan,Technologies%20make%20it%20in%20Louisiana.

[78] "Energy Department Selects 15 Projects to Advance Critical Material Innovations," US DOE, January 20, 2021, https://www.energy.gov/eere/amo/articles/energy-department-selects-15-projects-advance-critical-material-innovations.

[79] "Sodium-ion and Sodium Metal Batteries for Efficient and Sustainable Next Generation Energy Storage," European Commission, January 1, 2021, https://cordis.europa.eu/project/id/963542; "Scientists Develop Stable Sodium Battery Technology," National Science Foundation, January 6, 2022, https://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=304167&org=NSF&from=news; and Syl Kacapyr, "Engineers Reveal Cause of Key Sodium-ion Battery Flaw," Cornell University, February 11, 2022, https://news.cornell.edu/stories/2022/02/engineers-reveal-cause-key-sodium-ion-battery-flaw.

- **Providing capital to fuel innovation**: A major constraint for diversifying battery chemistries at scale is low availability of capital to develop the value chain. In the absence of investment from the private sector—which often is hesitant to shoulder risks for novel technologies—the United States and partner governments should leverage financing to fill investment gaps through such bodies as the US DOE's Loan Programs Office. In late 2020, during the Trump administration, the Loan Programs Office expanded its Advanced Technology Vehicles Manufacturing program's remit to include critical minerals, which facilitated the loan to US graphite producer Syrah Technologies in April 2022.[80] The DOE should capitalize on this change to accelerate funding to develop alternative battery chemistries as a means of reducing reliance on critical minerals. Specifically, the DOE should fund demonstration projects for alternative battery chemistries such as zinc-ion, which have received insufficient research and development funding.

- **Strategic shift on minerals**: The renewed US strategy on critical minerals has rightly sharpened focus on the issue of underdeveloped lithium-ion supply chains and the risk of input supply shortages.[81] This focus must be expanded, however, to include the development of mining and processing capacity for more abundant minerals to produce alternative battery chemistries, a strategy that is only just beginning to gain momentum within the US government's efforts to secure critical mineral supply chains.[82] As a corollary, minerals such as antimony, sodium, and iron should receive heightened attention for their role in diversifying the battery economy, and transition mineral supply strategies should be reviewed accordingly.

- **Incentives for "mineral switching"**: The unmatched performance of lithium-ion batteries has concentrated innovation and capitalization into this chemistry, enabling remarkable economies of scale that have brought down prices an astonishing 90 percent between 2010 and 2020.[83] Rolling out structured tax credits for diversifying battery material inputs—at the cell manufacturing stage of the value chain—could tip the scales for deploying alternatives to lithium-ion batteries at scale, such as sodium-ion batteries marketed for grid storage. Progress has been made in incentivizing growth of the energy storage sector overall, as illustrated in the expansion of tax credits available to stand-alone and commercial energy storage systems under the IRA.[84] While broadly useful, such a tax credit wouldn't necessarily offer incentives to opt for particular battery chemistries with diversified material inputs. Adapting such credits to support battery technologies that can demonstrate supply-side resiliency or target specific storage contexts for which alternative battery products might offer advantages would incentivize momentum for mineral switching and the resultant diversification of the battery storage supply base.

- **Reduce critical mineral usage**: Overall, policymakers should develop incentive structures to reduce reliance on the most supply-constrained mineral inputs. The Inflation Reduction Act serves as a landmark model for incentivizing investment in battery storage solutions and large segments of their value chain from mine to battery pack. However, the act places a premium on ensuring that critical mineral supply chains reach greater levels of maturity in the United States or certain allied countries. Policymakers should also develop a structure to incentivize a reduction in critical mineral usage overall, especially if such an approach complements the IRA's efforts to 'friend-shore' clean energy supply chains.

- **Targeting international partners**: Fully on-shoring entire supply chains is not always a feasible solution; however, collaboration with trusted partners across the mineral value chain can greatly reduce geopolitical risk. To this end, efforts like the US State Department's recently announced Minerals Security partnership, aimed at forging a coalition of like-minded economies committed to security of supply and sustainability throughout the mineral supply chain, should also recognize the utility of

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[80] "DOE Issues Notice of Guidance for Potential Loan Applicants Involving Critical Minerals," US DOE, December 1, 2020, https://www.energy.gov/articles/doe-issues-notice-guidance-potential-loan-applicants-involving-critical-minerals; and Keiron Greenhalgh, "US Critical Minerals Loan Applications Off to Slow Start," S&P Global, February 3, 2021, https://cleanenergynews.ihsmarkit.com/research-analysis/us-critical-minerals-loan-applications-off-to-slow-start.html.

[81] "Fact Sheet: Securing a Made in America Supply Chain for Critical Minerals"; and *Critical Minerals and Materials*, US DOE, 2021, https://www.energy.gov/sites/prod/files/2021/01/f82/DOE%20Critical%20Minerals%20and%20Materials%20Strategy_0.pdf.

[82] "Addressing the Threat to the Domestic Supply Chain from Reliance on Critical Minerals from Foreign Adversaries and Supporting the Domestic Mining and Processing Industries," Exec. Order No. 13953, 85 Fed. Reg. 62539 (2020), https://www.federalregister.gov/documents/2020/10/05/2020-22064/addressing-the-threat-to-the-domestic-supply-chain-from-reliance-on-critical-minerals-from-foreign; and "Fact Sheet: Securing a Made in America Supply Chain for Critical Minerals."

[83] Timothy Lee, "Battery Prices Have Fallen 88 Percent Over the Last Decade," *Ars Technica*, December 18, 2020, https://arstechnica.com/science/2020/12/battery-prices-have-fallen-88-percent-over-the-last-decade/; and "A Rapid Rise in Battery Innovation Is Playing a Key Role in Clean Energy Transitions," International Energy Agency, September 22, 2020, https://www.iea.org/news/a-rapid-rise-in-battery-innovation-is-playing-a-key-role-in-clean-energy-transitions.

[84] Liam Stocker, "Investment Tax Credit for Energy Storage Systems Over 5kWh in US Budget Proposal," *Energy Storage News*, September 14, 2021, https://www.energy-storage.news/investment-tax-credit-for-energy-storage-systems-over-5kwh-in-us-budget-proposal/; and US House Comm. on Ways and Means, "Subtitle F: Infrastructure Financing and Community Development," https://waysandmeans.house.gov/sites/democrats.waysandmeans.house.gov/files/documents/Section by Section Subtitle F%2C G%2C H%2C %26 J.pdf.

alternative battery designs.[85] Australia—which recently created a $1.41 billion facility for financing critical mineral resource development and with whom collaboration already exists through the US-Australia Critical Minerals Working Group—could be an invaluable partner in furthering development of cobalt-reducing batteries; the country could produce over one-quarter of the world's mined nickel by 2030, according to metals consultancy Roskill, based on the country's current projects.[86] Moreover, the need to diversify from standard lithium-ion chemistries can be raised within the various fora in which the US Departments of State and Energy collaborate with close strategic allies such as Canada, Japan, and the European Union.[87] Technical collaboration could also be pursued with countries such as the United Arab Emirates, which has pioneered large-scale energy storage projects such as a 108 megawatt sodium-sulfur battery installed for grid storage in Abu Dhabi.[88] Given the early stage of most alternative battery technologies, sharing engineering expertise is likely to be a necessity, not simply an accelerant, toward meeting demands for electrification.

- **Derisking resource development**: Core issues for mineral supply chains, such as access to capital, lie downstream of a sluggish permitting process, an ESG-conscious investment environment that is skeptical toward new extractive projects, and cost fundamentals that favor off-shoring upstream and midstream mineral production. In combination, these factors exacerbate the risks associated with investing in domestic mineral development. Such investments need to be derisked to provide access to political support, private capital, and public sources of funding. To date, the United States has relied extensively on the Defense Production Act (DPA) to provide some immediate support and financing to mineral supply chain activity in the United States, though it's highly unlikely that the DPA alone can fully provide the level of government support needed to sustain extensive domestic supply chain activity in the United States. Policymakers will likely need to go further by streamlining permitting and accelerating the process for supply-chain projects deemed critical to the national interest; and, if necessary, selectively using tariffs to protect against below-cost mineral dumping used by producers overseas to dislodge competitors. Such efforts will be critical to establishing a signal for capital markets to engage more directly in the mineral supply chain by improving certainty within the supply chain. Supply would be further bolstered by additional policy support to unlock ESG-aligned investment in the mining sector—likely through a collaboration with industry and environmental stakeholders to establish a sustainability taxonomy that can be applied to ongoing modernization of ESG scoring in other sectors.

While derisking resource development will positively impact the development of lithium-ion resources, it also will unlock access to minerals present in alternative chemistries such as Ambri's liquid-metal battery, which relies on the availability of antimony.

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[85] "Minerals Security Partnership," US Department of State, July 14, 2022, https://www.state.gov/minerals-security-partnership/.

[86] *Critical Minerals and Materials*, DOE; and Nickolas Zakharia, "Australia to Produce 25 Percent of the World's Nickel Supply," *Australian Mining*, February 8, 2021, https://www.australianmining.com.au/news/australia-to-produce-25-of-worlds-nickel-supply/.

[87] *Critical Minerals and Materials*, DOE.

[88] Steve Hanley, "Sodium Sulfur Battery in Abu Dhabi Is World's Largest Storage Device," *CleanTechnica*, February 3, 2019, https://cleantechnica.com/2019/02/03/sodium-sulfur-battery-in-abu-dhabi-is-worlds-largest-storage-device/.

CONCLUSION

As the energy transition from fossil fuels to low-carbon energy sources accelerates, energy storage will become an increasingly integral part of the equation for reducing the role of fossil fuels in the energy mix. Bringing large-scale energy storage solutions to the market as quickly, affordably, and effectively as possible will determine the success of efforts to decarbonize transportation and increase the share of wind and solar power in the energy system.

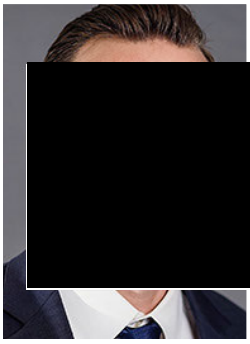
Batteries show great promise as a deployable and scalable solution that can be invaluable to overcoming the challenges of integrating new power sources into the grid. Battery electric vehicles are decarbonizing private and public transportation now and are poised to accelerate this process in the near future, forming the core of government and private-sector climate action in this vital, energy-intensive sector. Increasingly, batteries are also being deployed for stationary energy storage to enhance resiliency at the grid scale and for homes, data centers, and other energy consuming facilities that are becoming increasingly reliant on intermittent renewable energy and where power failure is not an option.

The supply chains that support battery deployment must therefore be derisked as much as possible to ensure continuity for the energy transition. As supply chains currently exist, such continuity is far from assured. While the public and private sector must work in concert to ensure secure supplies of critical minerals like lithium, cobalt, and graphite to strengthen economic and energy security in a global economy that aspires to reach net-zero emissions, contingencies must also be made should such supplies be disrupted or fail to match the rapid pace of increasing demand. Therefore, the raw material base for a battery sector that will be crucial in delivering an energy transition at scale must be diversified to the greatest extent possible to ensure the minimization of supply-chain bottlenecks.

The private sector, as well as governments, must contemplate their energy storage supply chains in a “just in case” scenario, rather than the “just in time” system that dominated the pre-pandemic world. Such a status quo was defined by older, ready-at-hand technologies rather than those for the energy transition or the mineral supply chains for the full weight of demand in a net-zero scenario. To rectify this, not only must supply chains for critical minerals be brought to a scale commensurate with the rapidly accelerating demands of the energy transition, but new technologies must also be embraced that can account for supply-chain risks, such as supply-chain access, resiliency, and sustainability. This must include an energy-storage sector flexible enough to accommodate different battery technologies for different uses, prioritizing considerations such as weight, energy density, and cost according to different use cases, such as transportation and stationary storage.

Ultimately, the key to a stable battery-storage systems sector will be a diversity of inputs that can enable the industry to continue to build out capacity even in the face of nearly inevitable supply constraints as demand grows in excess of the physical possibilities of new supply, while also protecting the overall sustainability of the battery supply chain. By understanding the variety of batteries that can be made available today, stakeholders can begin to build a resilient, diversified portfolio of mineral inputs that can weather even the worst-case scenario as demands on mineral supply chains continue to grow.

BIOGRAPHIES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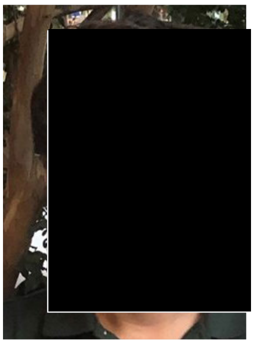
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Ryan was part of the Atlantic Council's inaugural Young Global Professionals class of spring 2021. Prior to joining the Council, he wrote for Britain's *The Spectator*, where he covered international trade and security and reported from Kazakhstan during its 2019 presidential election. He also served as Europe editor for Federal Network, a Capitol Hill-based press agency, where he led reporting on European Union institutions. During a brief hiatus from the Council, he worked as an energy and climate editor for London-based *Global Risk Insights*, and worked as a consultant on energy, technology, and agriculture in emerging and frontier markets. In addition to *The Spectator*, his work has been published by *Defense News*, *Energy Post*, and *Eurasianet*.

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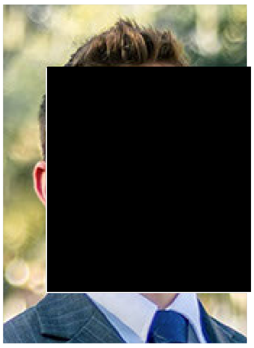
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ACKNOWLEDGMENTS

The Atlantic Council wishes to thank Perpetua Resources and ClearPath for supporting our work.

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[redacted]

GRID STORAGE LAUNCHPAD AT PNNL

OPENING FALL 2023

Validate | Accelerate | Collaborate

In 2018, the U.S. Department of Energy's Office of Electricity identified a national capability gap needed to accelerate the development and testing of new grid energy storage technologies that are more cost effective, safer, and more durable.

Grid energy storage is critical to a future resilient and flexible U.S. electric grid that will enable deep decarbonization of energy supply, ensure transition of cars from oil to electrons, and unlock a broad array of economic and societal benefits for all U.S. citizens.

• • • • •

In August 2019, the Department of Energy selected Pacific Northwest National Laboratory in Richland, Washington, as the site for a new $75 million facility called the Grid Storage Launchpad (GSL).

The GSL will provide systematic and independent validation of new grid storage technologies, from basic materials and components to prototypes, to accelerate the development and deployment of long-duration, low-cost grid energy storage. Strategic investments from the State of Washington, Battelle and PNNL provide additional support for GSL equipment, and research and development activities.

Research Directions

Through independent testing and validation of grid energy storage technologies, the GSL at PNNL will develop and promulgate rigorous grid performance standards and requirements that span the entire energy storage R&D development cycle — from basic materials synthesis to advanced prototyping. This mission focuses on three outcomes that address critical challenges in grid energy storage development:

- **Validate:** Independent testing of next generation storage materials and systems (<100kW) under realistic grid operating conditions
- **Accelerate:** Reduce risk and speed development of new technologies by propagating rigorous grid performance requirements to all stages of development
- **Collaborate:** Link DOE and storage R&D communities in a new collaboration center to solve key crosscutting challenges

- AUGUST **2019:** DOE selects PNNL as site for Grid Storage Launchpad
- AUGUST **2020:** Secretary of Energy visits PNNL to dedicate GSL site
- JULY **2020:** Solicitation for design-build contractor bids issued
- SPRING **2021:** Expected award of design-build contract
- SPRING **2022:** Expected groundbreaking
- FALL **2023:** Expected dedication and occupancy

Facility Cost Estimate: $75M

- **$28 million** in FY20 and FY21 from the DOE to fund facility design and initiate construction
- **Balance of funding** subject to future Congressional appropriations

Leveraged Funding: $35M

- **$20 million** in advanced research equipment and specialized instrumentation ($8 million from State of Washington, $7 million from PNNL, $5 million from Battelle)
- **$15 million** from PNNL in Lab-directed R&D support

Pacific Northwest
NATIONAL LABORATORY

INSIDE THE GRID STORAGE LAUNCHPAD

DISTINCTIVE CAPABILITIES IN A COLLABORATIVE FACILITY

Solutions to the pressing challenges of climate change, decarbonization, and power grid modernization require affordable, reliable, and safe energy storage deployed at scale. The U.S. Department of Energy’s Office of Electricity has selected Pacific Northwest National Laboratory in Richland, Washington, as the site for the Grid Storage Launchpad (GSL). The GSL will be a new, national research and development facility to accelerate the development of next-generation grid energy storage materials and technologies.

GSL Vitals

- **Estimated Facility Cost:** $75 Million
- **Leveraged Funding:** $35 Million from State of Washington, Battelle, Pacific Northwest National Laboratory

85,000 Square Feet

105 Workstations

30 Lab Modules

GSL Mission

- **Validate:** Independent testing of next-generation storage materials and systems (<100kW) under realistic grid operating conditions
- **Accelerate:** Reduce risk and speed development of new technologies by propagating rigorous grid performance requirements to all stages of development
- **Collaborate:** Link U.S. Department of Energy and storage research and development communities in a new collaboration center to solve key crosscutting challenges

1

[redacted]

New Materials

Novel approaches are used for materials discovery and synthesis using digital twins, physics-informed data models, and high-throughput experimentation.

2

[redacted]

In-Operando Characterization

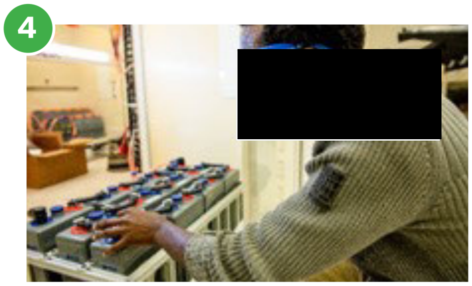
Specialized facilities, insulated from sound and vibration, are used to better understand the fundamental material properties of storage technologies during operation.

3

Advanced Prototyping

Advanced equipment is used to design and build advanced prototype batteries quickly for testing, thereby reducing cost and risk in advancing new approaches.

4



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Testing Capabilities

Specialized chambers for safely testing energy storage technologies from milliwatts to 100kW-scale under realistic grid duty cycles, use cases and operating conditions.

5

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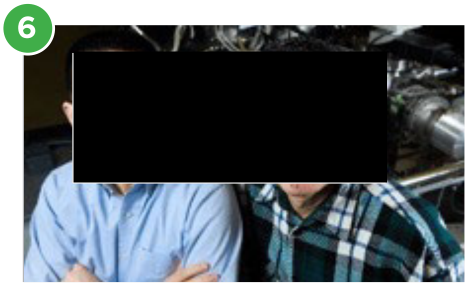
Visualization Laboratory

A visualization lab with multimedia audio-visual displays helps to analyze the role of energy storage in future grid scenarios and develop design criteria for new technologies.

6



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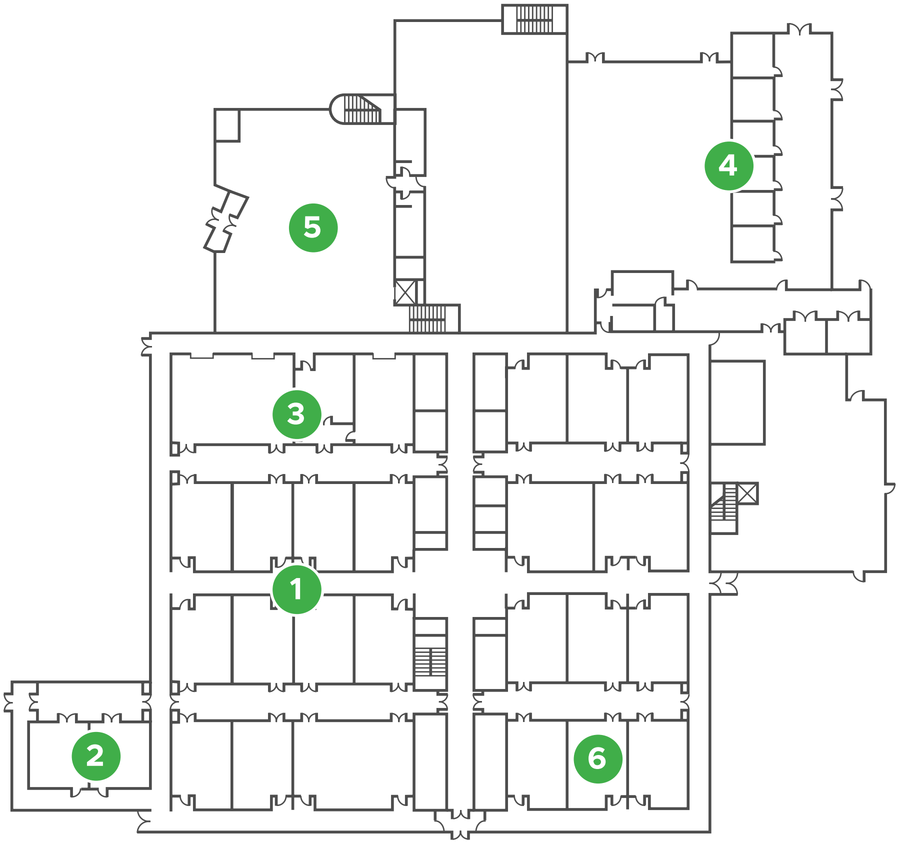
Fellowship Laboratories

Flexible, collaborative workspaces host materials scientists and energy storage researchers from around the world to advance promising technologies.



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NFCC
National Fire
Chiefs Council

The professional voice of the UK Fire & Rescue Service

Grid Scale Battery Energy Storage System planning – Guidance for FRS

Grid scale Battery Energy Storage Systems (BESS) are a fundamental part of the UK's move toward a sustainable energy system. The installation of BESS systems both in the UK and around the globe is increasing at an exponential rate. A number of high profile incidents have taken place and learning from these incidents continues to emerge.

In the UK, approval for the majority of BESS installations takes place through the Local Authority planning process. Fire and Rescue Services (FRSs) may be engaged throughout the planning process, but this is not a statutory requirement. However, the National Fire Chiefs Council would encourage early engagement with the local FRS, continuing throughout the planning process.

The NFCC's expectation is that a comprehensive risk management process must be undertaken by operators to identify hazards and risks specific to the facility and develop, implement, maintain and review risk controls. From this process a robust Emergency Response Plan should be developed.

Given the rapidly developing nature of the technology, and ever evolving understanding of risks and mitigation measures, there is a need for guidance to support FRSs in providing consistent and evidence-based contributions to the planning process.

The guidance does not seek to provide a full specification or opinion on the entirety of a BESS system design. Instead, the aim is to limit the content to such matters that directly relate to facilitating a safe and effective response, by the fire and rescue service, to a fire or vapour cloud release involving a BESS installation. This includes factors such as facilities for the fire and rescue service, and design factors that contribute to reducing the escalation in the severity of an incident.

This guidance relates specifically to grid scale (typically 1 MW or larger) BESS in open air environments, using lithium-ion batteries.

The guidance is based upon a range of supporting materials including academic research, national and international standards, case studies, and industry guidance. The content of this document is the result of analysis of that supporting material with subsequent professional judgement applied. Every BESS installation will be different and fire and rescue services should not limit themselves to the content of this guidance. Particular reference has been made to the following:

- State of Victoria (County Fire Authority) (2022), *Design Guidelines and Model Requirements: Renewable Energy Facilities*
- FM Global (2017) *Property Loss Prevention Data Sheets: Electrical Energy Storage Systems Data Sheet 5-33*
- NFPA (2023) *Standard for the Installation of Stationary Energy Storage Systems*

Further advice and guidance can be obtained through the NFCC Alternative Fuels and Energy Systems lead officer.

This document contains guidance on:

1. Information requirements
2. System design, construction, testing and decommissioning
3. Detection and monitoring
4. Suppression systems
5. Site access
6. Water supplies
7. Emergency plans
8. Environmental impacts
9. Recovery

Principles

This guidance has been developed with the safety of the public and emergency responders in mind. It is based on trying to help reduce the risk as far as reasonably practicable, whilst recognising that ultimate responsibility for the safe design and running of these facilities rests with the operator.

The guidelines are a starting point and cannot cover every eventuality or type of design.

In developing these guidelines the hazards and risks from lithium-ion batteries, identified in National Operational Guidance, has been considered.

The following principles should be considered by Fire Services, when liaising with owners and operators, and form the basis of this guidance[1]:

1. Effective identification and management of hazards and risks specific to the siting, infrastructure, layout, and operations at the facility.
2. Impact on surrounding communities, buildings, and infrastructure.
3. Siting of renewable energy infrastructure so as to eliminate or reduce hazards to emergency responders.
4. Safe access for emergency responders in and around the facility, including to renewable energy and firefighting infrastructure.

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[1] State of Victoria (County Fire Authority) (2022), *Design Guidelines and Model Requirements: Renewable Energy Facilities*, p.4

5. Provision of adequate water supply and firefighting infrastructure to allow safe and effective emergency response.
6. Vegetation sited and managed so as to avoid increased bushfire and grassfire risk.
7. Prevention of fire ignition on-site.
8. Prevention of fire spread between site infrastructure (solar panel banks, wind turbines, battery containers/enclosures).
9. Prevention of external fire impacting and igniting site infrastructure.
10. Provision of accurate and current information for emergency responders during emergencies.
11. Effective emergency planning and management, specific to the site, infrastructure and operations.
12. Owner to have a comprehensive Emergency Response Plan, showing full understanding of hazards, risks, and consequences.

Information Requirements

Grid scale BESS should form part of FRS planning in accordance with arrangements required under section 7(2)(d) of the Fire and Rescue Services Act (2004). Site Specific Risk Information (SSRI) should be made available to crews in the form of an effective Emergency Response Plan.

Details of any site access arrangements, such as key codes, should be provided to the FRS.

System design, construction, testing and decommissioning

Information is required as early as possible from the applicant /developer/designer/manufacturer etc., to allow an initial appraisal of the BESS to be made. This information should be provided to the FRS (via the Local Authority Planners in the first instance), with appropriate evidence provided to support any claims made on performance, and with appropriate standards cited for installation.

Such information should also be made available to FRSs for inclusion in Site Specific Risk Information (SSRI) records.

System design and construction

Information required:

1. The battery chemistries being proposed (e.g. Lithium-ion Phosphate (LFP), Lithium Nickel Manganese Cobalt Oxide (NMC)). Because:
    a. Battery chemistries will directly affect the heat released when a cell goes into thermal runaway[2]
    b. Battery chemistries will influence vapour cloud formation.

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[2] https://www.nasa.gov/sites/default/files/atoms/files/nabw20_fire_gas_char_studies_liion_cells_batt_djuarez-robles.pdf

    c. An understanding of the battery chemistry is useful when requesting scientific advice during an incident.
2. The battery form factor (e.g. cylindrical, pouch, prismatic)
3. Type of BESS e.g. container or cabinet
4. Number of BESS containers/cabinets
5. Size/capacity of each BESS unit (typically in MWh)
6. How the BESS units will be laid out relative to one another.
7. A diagram / plan of the site.
8. Evidence that site geography has been taken into account (e.g. prevailing wind conditions).
9. Access to, and within, the site for FRS assets
10. Details of any fire-resisting design features
11. Details of any:
    a. Fire suppression systems
    b. On site water supplies (e.g. hydrants, EWS etc)
    c. Smoke or fire detection systems
    d. Gas detection systems
    e. Temperature management systems
    f. Ventilation systems
    g. Exhaust systems
    h. Deflagration venting systems
12. Identification of any surrounding communities, sites, and infrastructure that may be impacted as a result of an incident.

Testing

Details of any evidence based testing of the system design should be requested, for example, conformity with UL 9540A Test Method.

Design

Design features should be made clear. These may include:

- Rack layout and setup
- Thermal barriers and insulation
- Container layout and access arrangements

Detection and monitoring

An effective and appropriate method of early detection of a fault within the batteries should be in place, with the ability to disconnect the affected battery/batteries remotely. This may be achieved automatically through the provision of an effective Battery Management System (BMS).

Should thermal runaway conditions be detected then there should be the facility in place for the early alerting of emergency services.

Detection systems should also be in place for alerting to other fires that do not involve thermal runaway (for example, fires involving electrical wiring).

Continuous combustible gas monitoring within units should be provided. Gas detectors should alarm at the presence of flammable gas (yes/no), shut down the ESS, and cause the switchover to full exhaust of the ventilation system[3]. Gasses produced during a thermal runaway event can be lighter and/or heavier than air and, as such, the location of sensors should take this into account.

External audible and visual warning devices (such as cabinet level strobing lights), as well as addressable identification at control and indicating equipment, should be to linked to:

1. Battery Management System (when a thermal runaway event is identified)
2. Detection and suppression system activation

This will enable first responders to understand what the warning is in relation to. This will aid in their decision-making.

Suppression systems

Suitable fixed suppression systems should be installed in units in order to help prevent or limit propagation between modules.

Where it is suggested that suppression systems are not required in the design, this choice should be supported by an evidence based justification and Emergency Response Plan that is designed with this approach in mind (for example, risk assessed controlled burn strategies, and external sprinkler systems).

Whilst gaseous suppression systems have been proposed previously, current research indicates the installation of water based suppression systems is more effective.

FM Global cite the following reasons for not recommending gaseous protection systems[4]:

1. **Efficacy relative to the hazard**. As of 2019, there is no evidence that gaseous protection is effective in extinguishing or controlling a fire involving energy storage systems. Gaseous protection systems may inert or interrupt the chemical reaction of the fire, but only for the duration of the hold time. The hold time is generally ten minutes, not long enough to fully extinguish an ESS fire or to prevent thermal runaway from propagating to adjacent modules or racks.
2. **Cooling**. FM Global research has shown that cooling the surroundings is a critical factor to protecting the structure or surrounding occupancy because there is currently no way to

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[3] FM Global (2017) *Property Loss Prevention Data Sheets: Electrical Energy Storage Systems*, para. 2.5.5.2
[4] FM Global (2017) *Property Loss Prevention Data Sheets: Electrical Energy Storage Systems*, para. 3.3

extinguish an ESS fire with sprinklers. Gaseous protection systems do not provide cooling of the ESS or the surrounding occupancy.

3. **Limited Discharge**. FM Global research has shown that ESS fires can reignite hours after the initial event is believed to be extinguished. As gaseous protection systems can only be discharged once, the subsequent reignition would occur in an unprotected occupancy

The choice of a suppression system should be informed by liaison with a competent system designer who can relate the system choice to the risk identified and the duration of its required activation. Such a choice must be evidence based.[5]

Any calculations for sufficient water supply for an appropriate suppression system will need to be completed by a competent person considering the appropriate risk and duration of any fire.

Water run-off and potential impact on the environment, along with mitigation measures, should be considered and detailed in the Emergency Response Plan.

Lack of sufficient water supplies at a particular site location should not be considered as the basis for a suppression system choice. Such an approach could result in potentially ineffective and/or dangerous system designs.

Deflagration Prevention and Venting

BESS containers should be fitted with deflagration venting and explosion protection appropriate to the hazard. Designs should be developed by competent persons, with design suitability able to be evidenced.[6] Exhaust systems designed to prevent deflagration should keep the environment below 25% of Lower Explosive Limit (LEL).

Flames and materials discharged as a result of any venting should be directed outside to a safe location and should not contribute to any further fire propagation beyond the unit involved. The likely path of any vented gasses or materials should be identified in Emergency Response Plans to reduce risk to responders.

Explosion/deflagration strategies should be built into the emergency plan such that responders are aware of their presence and the impact of their actions on these strategies.[7]

Where emergency ventilation is used to mitigate an explosion hazard, the disconnect for the ventilation system should be clearly marked to notify personnel or first responders to not disconnect the power supply to the ventilation system during an evolving incident.[8]

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[5] NFPA (2023) *Standard for the Installation of Stationary Energy Storage Systems*, para C.3

[6] BS EN 16009:2011 *Flameless Explosion Venting Devices*; BS EN 14373:2021 *Explosion Suppression Systems*; BS EN 14797:2007 *Explosion Venting Devices*.

[7] UL FRSI (2020) *Four Firefighters Injured in Lithium-ion Battery Energy Storage System Explosion – Arizona*, pp. 47-49

[8] NFPA (2023) *Standard for the Installation of Stationary Energy Storage Systems*, para G.1.4.3.3

Access

Site access

Suitable facilities for safely accessing and egressing the site should be provided. Designs should be developed in close liaison with the local FRS as specific requirements may apply due to variations in vehicles and equipment.

This should include:

- At least 2 separate access points to the site to account for opposite wind conditions/direction.
- Roads/hard standing capable of accommodating fire service vehicles in all weather conditions. As such there should be no extremes of grade.
- A perimeter road or roads with passing places suitable for fire service vehicles.
- Road networks on sites must enable unobstructed access to all areas of the facility.
- Turning circles, passing places etc size to be advised by FRS depending on fleet.

Access between BESS units and unit spacing

In the event of a fire involving a BESS unit, one of the primary tactics employed will be to prevent further unit to unit fire spread. Suitable access for firefighters to operate unimpeded between units will therefore be required. This should allow for the laying and movement of hose lines and, as such, access should be free of restrictions and obstacles. The presence of High Voltage DC Electrical Systems is a risk and their location should be identified. Exclusion zones should be identified.

A standard minimum spacing between units of 6 metres is suggested[9] unless suitable design features can be introduced to reduce that spacing. If reducing distances a clear, evidence based, case for the reduction should be shown.

Any reduction in this separation distance should be design based by a competent fire engineer. There should be consideration for the fire separation internally and the total realistic load of fire. Proposed distances should be based on radiant heat flux (output) as an ignition source.

The NFCC does not support the stacking of containers/units on top of one another on the basis of the level of risk in relation to fire loading, potential fire spread, and restrictions on access.

Distance from BESS units to occupied buildings & site boundaries

Individual site designs will mean that distances between BESS units and occupied buildings/site boundaries will vary. Proposed distances should take into account risk and mitigation factors. However, an initial minimum distance of 25 metres is proposed prior to any mitigation such as blast walls. Where possible buildings should be located upwind.

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[9] FM Global (2017) *Property Loss Prevention Data Sheets: Electrical Energy Storage Systems*, para. 2.3.2.2

Site Conditions

Sites should be maintained in order that, in the event of fire, the risk of propagation between units is reduced. This will include ensuring that combustibles are not stored adjacent to units and access is clear and maintained. Areas within 10 metres of BESS units should be cleared of combustible vegetation and any other vegetation on site should be kept in a condition such that they do not increase the risk of fire on site. Areas with wildfire risk or vegetation that would result in significant size fires should be factored into this assessment and additional cleared distances maintained as required.

Water Supplies

Water supplies will depend on the size of the installation. In the majority of cases, initial firefighting intervention will focus on defensive firefighting measures to prevent fire spread to adjacent containers. As a result, proposals for water supplies on site should be developed following liaison with the local fire and rescue service taking into account the likely flow rates required to achieve tactical priorities. This should also take account of the ability of/anticipated time for the fire and rescue service to bring larger volumes of water to site (for example through the provision of High Volume Pumps).

IP ratings of units should be known so that risks associated with boundary cooling can be understood.

As a minimum, it is recommended that hydrant supplies for boundary cooling purposes should be located close to BESS containers (but considering safe access in the event of a fire) and should be capable of delivering no less than 1,900 litres per minute for at least 2 hours. Fire and rescue services may wish to increase this requirement dependant on location and their ability to bring supplementary supplies to site in a timely fashion.

Water supply for any automatic suppression system will be covered by the relevant standard/design depending on which system chosen as appropriate for the risk. For manual water, amounts should come from performance based requirement rather than a reference to a code, unless it can be proven that the code specifically covers BESS. Regarding water storage tanks, volumes will again need to be informed on a performance-based need. Isolation points should be identified.

Any static water storage tanks designed to be used for firefighting must be located at least 10 metres away from any BESS container/cabinet. They must be clearly marked with appropriate signage. They must be easily accessible to FRS vehicles and their siting should be considered as part of a risk assessed approach that considers potential fire development/impacts. Outlets and connections should be agreed with the local FRS. Any outlets and hard suction points should be protected from mechanical damage (e.g. through use of bollards).

Consideration should be given, within the site design, to the management of water run-off (e.g. drainage systems, interceptors, bunded lagoons etc).

Signage

Signage should be installed in a suitable and visible location on the outside of BESS units identifying the presence of a BESS system. Signage should also include details of:

- Relevant hazards posed
- The type of technology associated with the BESS
- Any suppression system fitted
- 24/7 Emergency Contact Information

Signs on the exterior of a building or enclosure should be sized such that at least one sign is legible at night at a distance of 30 metres or from the site boundary, whichever is closer[10].

Adherence to the Dangerous Substances (Notification and Marking of Sites) Regulations 1990 (NAMOS) should be considered where the total quantity of dangerous substances exceeded 25 tonnes.

Emergency Plans

Commented [MD1]: Should we consider a premise information box at the site entrance for large sites ?

Site operators should develop emergency plans and share these with the Fire and Rescue Service. These include:

A Risk Management Plan should be developed by the operator, which provides advice in relation to potential emergency response implications including:

- The hazards and risks at and to the facility and their proposed management.
- Any safety issues for firefighters responding to emergencies at the facility.
- Safe access to and within the facility for emergency vehicles and responders, including to key site infrastructure and fire protection systems.
- The adequacy of proposed fire detection and suppression systems (eg., water supply) on-site.
- Natural and built infrastructure and on-site processes that may impact or delay effective emergency response.

An Emergency Response Plan should be developed to facilitate effective and safe emergency response and should include:

Commented [VB2]: Site isolation points
Number of life risk during day/night
Private Hydrant locations
A list of what the BESS supplies power to?

- How the fire service will be alerted
- A facility description, including infrastructure details, operations, number of personnel, and operating hours.
- A site plan depicting key infrastructure: site access points and internal roads; firefighting facilities (water tanks, pumps, booster systems, fire hydrants, fire hose reels etc); drainage; and neighbouring properties.

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[10] NFPA (2023) *Standard for the Installation of Stationary Energy Storage Systems*, para G.1.4.2.1.1

- Details of emergency resources, including fire detection and suppression systems and equipment; gas detection; emergency eye-wash and shower facilities; spill containment systems and equipment; emergency warning systems; communication systems; personal protective equipment; first aid.
- Up-to-date contact details for facility personnel, and any relevant off-site personnel that could provide technical support during an emergency.
- A list of dangerous goods stored on site.
- Site evacuation procedures.
- Emergency procedures for all credible hazards and risks, including building, infrastructure and vehicle fire, grassfire and bushfire

Environmental impacts

Suitable environmental protection measures should be provided. This should include systems for containing and managing water runoff. System capability/capacity should be based on anticipated water application rates, including the impact of water based fixed suppression systems.

Sites located in flood zones should have details of flood protection or mitigation measures.

Recovery

The operator should develop a post-incident recovery plan that addresses the potential for reignition of ESS and de-energizing the system, as well as removal and disposal of damaged equipment.[11]

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[11] FM Global (2017) *Property Loss Prevention Data Sheets: Electrical Energy Storage Systems*, para. 2.8.2.3

Journal of Loss Prevention in the Process Industries 82 (2023) 104998

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

Performance-based assessment of an explosion prevention system for lithium-ion based energy storage system

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ARTICLE INFO

Keywords:
BESS
CFD
Explosions
Explosion prevention

ABSTRACT

This work developed and analyzed a design methodology for Powin Stack™ 360 enclosures to satisfy the requirements for explosion prevention per NFPA 855. Powin Stack™ 360 enclosures are lithium-ion-based stationary energy storage systems (ESS). The design methodology consists of identifying the hazard, developing failure scenarios, and providing mitigation measures to detect the battery gas and maintain its global concentration lower than 25% of the lower flammability limit (LFL) to meet the prescriptive performance criterion of NFPA 69 – Standard on Explosion Prevention Systems. The UL 9540A test data is used to define the battery gas composition, release rate, and release duration to describe the failure scenario involving thermal runaway propagation. The ESS enclosure consists of individual stacks (compartments) with targeted airflow to ensure the cooling of batteries during normal operational conditions. This arrangement makes it difficult to use a standard exhaust ventilation methodology to design an explosion prevention system. An innovative approach is used to purge the battery gas from individual Powin Stacks™ and from the main enclosure during a thermal runaway event. The designed method is analyzed using a computational fluid dynamics (CFD) model to ensure it meets the intent of NFPA 69. The explosion prevention system functionality presented in this work is limited to removing flammable battery gas generated due to the non-flaring decomposition of batteries and does not consider its interactions with other fire protection features.

1. Introduction

Energy storage is playing a pivotal role in empowering the decarbonization of transportation and enabling power grids to function with more resilience. Lithium-ion-based batteries have come a long way from their usage in consumer electronics with tens of Wh (watt-hour) capacity to approximately 100 kWh capacity battery systems in modern electric vehicles (Bisschop et al., 2020). Decarbonizing the electricity generation process is a big issue and critical to supporting the changing landscape in the automotive industry. Addressing this issue ensures we do not deal with greenhouse gases at the electricity generation source. Lithium-ion-based energy storage is one of the leading technologies for sustainable and emission-free energy. The advantage of storing green energy, such as solar or wind, during off-peak hours and using it during peak hours is gaining traction as various governments in the world look toward renewable energy sources. The growth in the energy capacity is tremendous, with the United States having less than 1 GW of large energy storage installations in 2019 to adding a capacity of 6 GW in 2021 and forecasted to achieve an additional 9 GW in 2022 (Blunt and Hiller, 2021).

Like many other energy sources, Lithium-ion-based batteries present some hazards related to fire, explosion, and toxic exposure risks (Gully et al., 2019). Although the battery technology can be operated safely and is continuously improving, the battery cells can undergo thermal runaway when they experience an exothermic reaction (Balakrishnan et al., 2006) of the internal cell components leading to a sudden release of thermal and electrochemical energy to the surroundings. These reactions cause thermal runaway occur when the internal separator of the anode and cathode is compromised due to some abuse of the cell (Ghiji et al., 2021; Roth et al., 2007) Cyclical thermal/electrical loading and unloading, manufacturing defects, and thermal, mechanical, or electrical abuse are many reasons that can cause cell degradation leading to

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https://doi.org/10.1016/j.jlp.2023.104998
Received 30 June 2022; Received in revised form 20 December 2022; Accepted 24 January 2023

thermal runaway (Bravo Diaz et al., 2020).

As the ESS enclosures are installed at an accelerating rate, a few incidents related to fires and explosions (Zalosh et al., 2021) have occurred. A detailed publicly available database on ESS failure events is maintained by the Electric Power Research Institute (EPRI) that provides a good overview of system capacity, age, event date, and its state during the accident (Long, 2022). The ESS community continues to learn from these incidents, and a lot of progress has been made to ensure the safety of these systems. NFPA 855 (NFPA, 2020) standard now requires ESS installation shall be provided with either an explosion control system, i. e., deflagration vents according to NFPA 68 (NFPA, 2018), or an explosion prevention system, i.e., a mechanical ventilation system according to NFPA 69 (NFPA, 2019). Essentially all ESS installations in the U.S. are required to have some form of explosion control unless the omission is demonstrated by large-scale testing. This paper focuses on developing a procedure to design an explosion prevention system for the Powin Stack™ 360 enclosure.

While the scope of NFPA 69 is extensive and applies to the design, installation, operation, maintenance, and testing of systems to prevent explosions using a variety of methods, this work is limited to the conceptual design of an explosion prevention system by pursuing the performance-based design option that aims at controlling the released battery gas combustible concentration. The system is designed using computational fluid dynamics (CFD) that helps in understanding the dispersion of battery gas within the enclosure. The usage of CFD for simulating an accidental release of flammable gas is well established. The CFD simulations can help demonstrate the evolution of gas release as a function of space and time.

Various metrics can be used to quantify the global parameters, such as volume fraction and mass within an enclosure. In addition, displaying the gas cloud between the lower flammability limit (LFL) and upper flammability limit (UFL) can help quantify the size of the flammable cloud. This detailed information is very useful in understanding the consequence of a scenario and designing the mitigation measures such as gas detection and explosion prevention systems.

The usage of CFD for designing explosion prevention systems is prevalent in process safety industries dealing with flammable fluids (Shen et al., 2020) and explosible dust (Eckhoff, 2009). Different scenarios involving spills, buoyancy-driven leaks, momentum-driven leaks, and a sudden loss of containment can be prescribed using a source term in the CFD model. These different leak scenarios require a deep understanding of the flammable fluid, storage and operating conditions, and the associated hazards. The critical challenge in designing an explosion prevention system for a ESS is to quantify the source term that can describe the release of battery gas during a thermal runaway event. The highly non-linear and stochastic behavior of battery cells requires a different approach from other failure scenarios commonly seen in the process safety industry, with greater emphasis on the availability of UL 9540A test (ANSI/CAN/UL, 2019) data to describe a battery gas release rate. In addition, the released battery gas is a mixture of hydrogen, carbon dioxide, carbon monoxide, and several hydrocarbons (Fernandes et al., 2018), requiring an approach to quantify mixture properties and flammability limits. Furthermore, the HVAC system used to cool the batteries can impact airflows with the formation of hot and cold aisles that can impact the placement of gas detectors as well as supply and exhaust locations for the explosion prevention system.

2. Design approach

2.1. Applicable standards

NFPA 855 (NFPA, 2020) requires that an explosion prevention system be installed in accordance with NFPA 69 (NFPA, 2019) for buildings and walk-in containers housing an ESS. NFPA 855 also indicates that a UL 9540A test or equivalent full-scale fire test shall be performed to evaluate the fire characteristics of an ESS that undergoes thermal runaway. NFPA 69 requires that the global combustible concentration shall be maintained at or below 25% of the LFL for all foreseeable variations in operating conditions and material loadings. The typical method to achieve this criterion is to use a ventilation/purge system that removes flammable battery gas from the container housing the ESS and replenishes it with outside clean air. For compliance with NFPA 855/NFPA 69 requirements to limit the flammable gas concentration, a representative release rate of battery gas during a thermal runaway scenario is required for the input to the explosion prevention analysis.

2.2. Design inputs related to the thermal runaway failure scenario

2.2.1. UL 9540A thermal runaway testing

NFPA 855 recommends that a UL 9540A (ANSI/CAN/UL, 2019) test be used to evaluate the fire characteristics of an ESS undergoing thermal runaway for explosion control safety systems. An approach to determine a flammable battery gas source term to design explosion control systems has been developed based on UL 9540A or similar test data. This approach aims to ensure that the process is consistent regardless of the battery system being evaluated. Information from the cell, module, and unit level UL 9540A test reports, or similar test data available, is used to calculate the composition, properties, amount, and duration of the flammable gas release.

The UL 9540A cell-level test defines a repeatable method for forcing a battery cell into thermal runaway. The standard requires measurements of the cell surface temperature as well as the temperature of the gas released from the cell during testing. Other important parameters used in the source term model include the gas volume released, gas composition, gas lower flammability limit, and the thermal runaway temperature of the cell which are measured as part of cell testing. (ANSI/CAN/UL, 2019). The reported thermal runaway temperature is the average of four tests. In a fifth cell test the gas volume and composition from the cell is measured. In separate testing, the previously measured composition of the gas is synthetically replicated and used to determine the LFL, burning velocity, and maximum explosion pressure.

The module- and unit-level UL 9540A tests are required if the cell vent gas composition is flammable according to ASTM E918 (2011). As over 90% of large scale ESS installations use lithium-ion batteries (U.S. Energy Information Administration, 2021), which contain flammable liquid electrolytes and release flammable gases during a thermal runaway event, module and unit level tests must be performed. One or more cells in the initiating module are forced into thermal runaway using the same or similar methodology used in the cell-level test. For the development of the source term, the extent and timing of thermal runaway propagation in the module and unit are used to construct an appropriate rate and duration of flammable gas release.

Additional conservatism may be added to the source term to account for the various types of uncertainty present in this analysis. This includes test-to-test variability, the thermal runaway initiation method, and conditions compared to an actual scenario, as well as general experimental uncertainty. For example, different thermal runaway initiation methods can yield more or less released gas from the cell (Essl et al., 2020). To add conservatism to the source term, the actual cell release volume and gas composition are used in combination with a shorter time to propagate thermal runaway. This method results in a higher overall average gas release rate than using the overall timing from the UL 9540A test.

2.2.2. Representative Powin Stack™ 360 ESS enclosure

A representative 53-ft Powin Stack™ 360 ESS enclosure was used for the CFD analysis. The overall dimensions of this enclosure are 53 feet long, 8 feet wide, and 9.5 feet high. This enclosure contains 14 Powin Stacks™ and a non-habitable control room at one of its ends. The two HVAC inlet ducts run the length of the container at the top, with ducting and cable racks present above the battery stacks. A cut section of the ESS enclosure provides details of the ESS interior in Fig. 1.

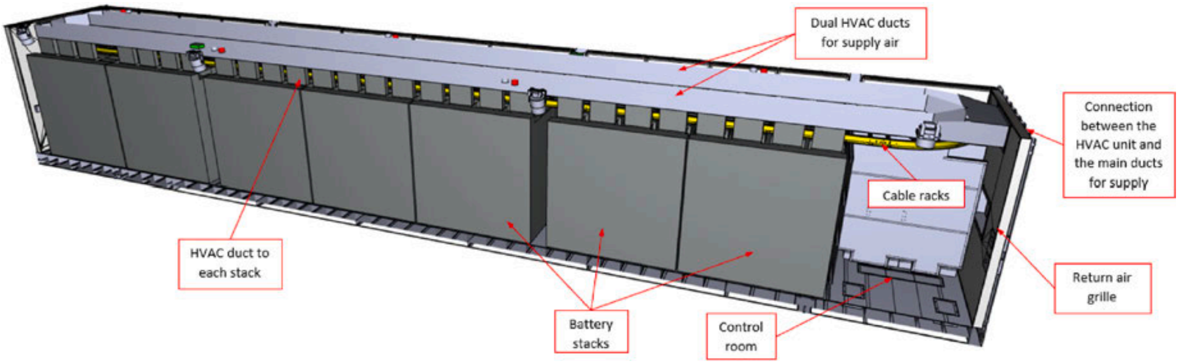

Fig. 1. Powin Stack™ 360 enclosure interior with battery stack layout and other internal equipment.

Each of the 14 Powin Stacks™ consists of 2 separate half stacks in their left and right cabinets, as illustrated in Fig. 2, housing the battery packs and the battery management system (BMS). There are 23 battery packs, with each battery pack consisting of 2 battery modules. The Powin Energy Stack 360 module consists of nine prismatic LFP cells. Each Powin Stack ™ has a total of 16 stack fans, 8 for each half of the stack, which provide airflow into the Powin Stacks™. These stack fans at the top are connected to the main HVAC supply duct of the ESS enclosure.

The airflow pattern within the battery stack is illustrated in Fig. 3. The total airflow rate is 800 CFM (0.38 m^3/s) from the eight stack fans for each half of the stack. Airflow to the stack fans is ducted from one of the two main HVAC supply ducts. Air exchange between the cold aisle and hot aisle is only through the battery module. As designed for this work, stack fans get activated by the BMS if a cell temperature goes higher than T_{th}[1] inside the battery module. Activation of the stack fans based on cell temperature would imply that the stack fans are operating at their full capacity prior to an accidental battery gas release. These fans are then assumed to be running before the cells undergo thermal runaway and are assumed to be running throughout the battery gas release duration. This HVAC configuration is noted as “HVAC ON” in this work.

2.2.3. *Powin Stack™ 360 ESS enclosure HVAC system*

The ESS container is equipped with two external self-contained wall-mounted HVAC units located on both ends of the container (see one HVAC unit connection illustrated in Fig. 1). Depending on indoor/outdoor environmental conditions, the HVAC units can function as.

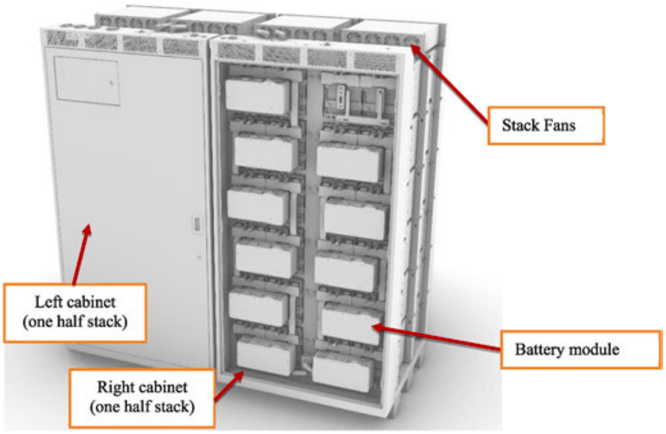

Fig. 2. Powin Stack™ 360 geometry.

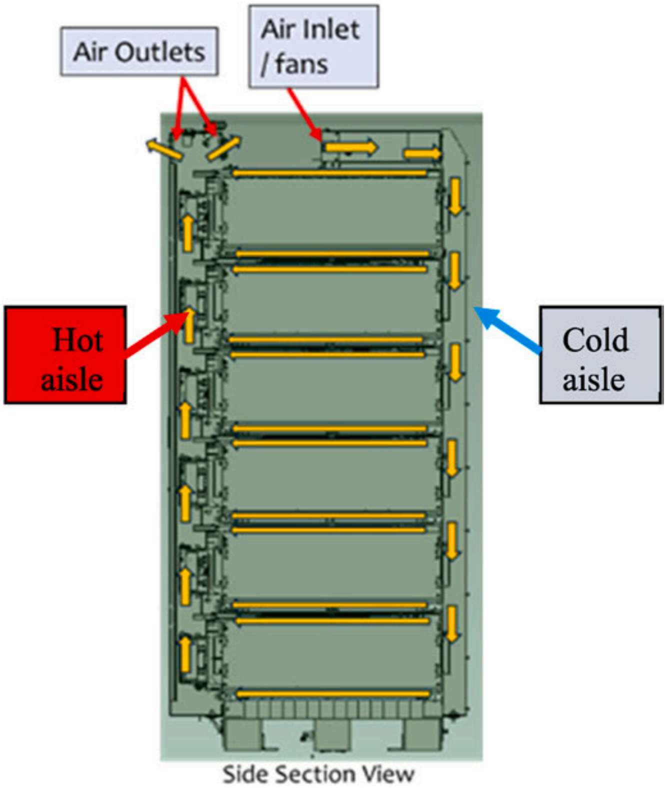

Fig. 3. Airflow pattern within the stack.

a) a 100-percent recirculation mode: no outside air is introduced in the enclosure while the air already inside is conditioned, or
b) a 100-percent economizer mode: outside air is conditioned and supplied into the enclosure, and an equivalent amount of inside air is exhausted to the exterior.

A diagram of these two HVAC modes (Marvair, n.d.) is shown in Fig. 4. Fig. 5 illustrates the air coming from the main ducts is connected to both HVAC units, enters via stack fans, and sweeps through each of the 14 stacks (batteries not shown) before getting out of the stacks by outlets located at the top.

2.2.4. *Powin Stack™ 360 ESS enclosure explosion prevention system*

Fig. 6 illustrates the components of the battery gas explosion prevention system of the Powin Stack™ 360 ESS container. Battery gas

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[1] T_{th} is a threshold temperature much lower than the thermal runaway temperature.

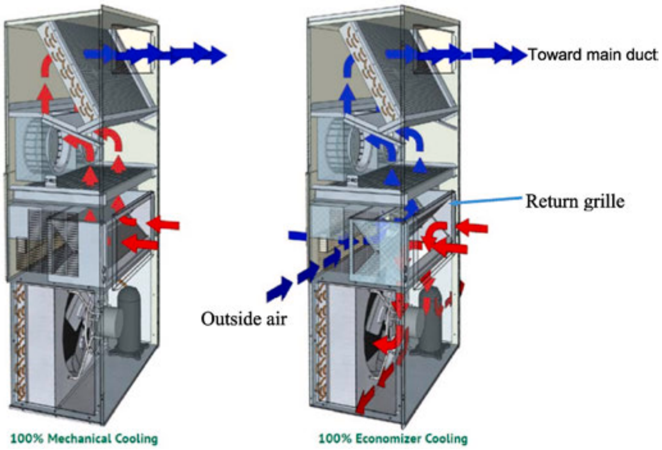


Fig. 4. Ventilation modes of the HVAC system.

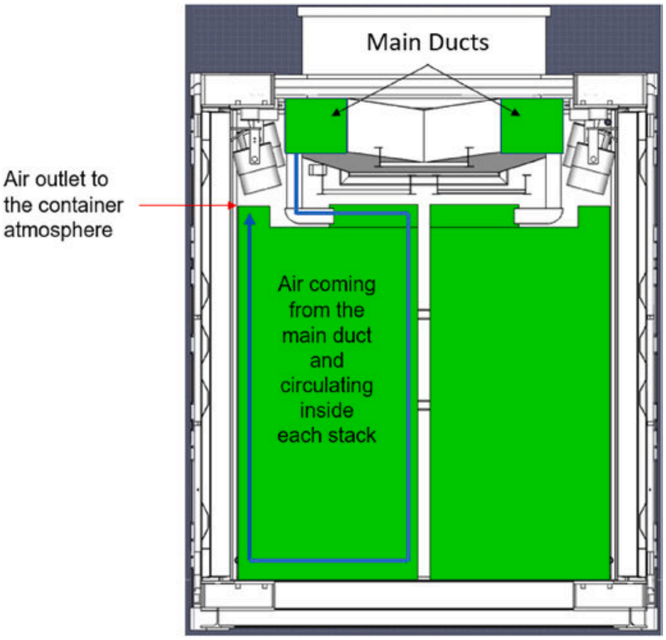


Fig. 5. Air transfer between one of the 14 stacks and the BESS enclosure atmosphere.

released during a thermal runaway event would be detected by one of the two hydrogen detectors located on the upper part of the container as shown in Fig. 6. After the hydrogen concentration (volume fraction) at one of the detectors reaches 0.1% (or 2.5% H_2 LFL), the activation of the explosion prevention system is assumed in this work to have a response time of 90 s. It should be noted that the explosion prevention system corresponds to the HVAC system in economizer mode. Fresh air at 3800 CFM (1.79 m^3/s) flowing through the dual HVAC longitudinal duct will sweep through the stacks before entering the main enclosure; this increased amount of the air inside the enclosure will cause the enclosure atmosphere containing battery gas to be exhausted outside via the two HVAC unit return grilles. In addition, the BMS ensures the 1600 CFM (0.76 m^3/s) (800 CFM (0.38 m^3/s) to each half) is directed to the stack with a cell temperature higher than the $T_{th,}$ and the rest of the 2200 CFM (1.04 m^3/s) is distributed among the remaining stacks.

2.2.5. *Flammable battery gas release model*

Most UL 9540A data commissioned by manufacturers is proprietary. For this work, a set of representative thermal runaway data for a lithium iron phosphate ($LiFePO_4$) chemistry battery cell was used to develop the input flammable gas model for the CFD model. Based on the cell-level test, the battery gas composition is found to be as reported in Table 1. This battery gas is released at a temperature of 640 °C. The LFL of the battery gas was estimated for this work to be 6.14% based on testing the representative gas mixture at ambient conditions. The “safe” threshold considered in the analysis presented in this work is 25% of this LFL or 1.54%.

The module-level test is used to quantify the release rate of battery gas. Table 2 summarizes the characteristics of the two failure events considered in this work.

1. A single-module failure scenario is developed using the UL 9540A test data associated with a battery gas release of 1.65 g/s.
2. A two-module failure scenario is associated with a source term of 2.0 g/s.

The battery gas release rate scenarios were based on an analysis of UL 9540A test data using the approach outlined in Section 2.2.1. The scenarios were selected based on elevated temperatures (higher than the thermal runaway temperature) in cells in the modules. The timing of thermal runaway within a single module is based on an approximation of the realistic minimum propagation delay from observations during the testing.

Table 1
Battery gas composition from prismatic cell based on UL9540A test data.

Species	Vol. Percent
Hydrogen	48.69%
Carbon Dioxide	28.70%
Carbon Monoxide	9.86%
Hydrocarbons[a]	12.75%

[a] Hydrocarbons are assimilated to propane in the following CFD sections.

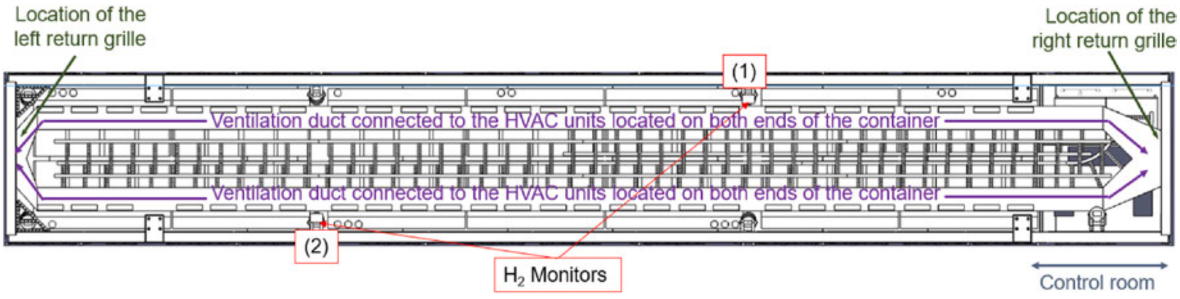


Fig. 6. Enclosure showing hydrogen detector location and HVAC exhaust locations.

Table 2
Characteristics of the Powin Stack™ 360 ESS container failure events.

Event Description	Number of Cells involved	Failure Mode	Average gas release rate (g/s)	Total duration (min.)	Assumptions
Single-module failure	9	Cell overheating or power surge affecting one module	1.65	14.5	Propagation to all cells in one module in series (five cells) & parallel (two cells in a thermal runaway at one time)
Two-module failure	18	Cell overheating or power surge affecting two modules	2.0	24	Propagation to the second module occurs at 550 s (half the median time to 200 °C in the module level tests)

2.3. *Design tool*

The design tool used in this work is a CFD model called Fire Dynamics Simulator (FDS) (McGrattan et al., August 21). FDS is a computer fire model developed by the National Institute of Standards & Technology (NIST). For the type of analysis performed in the work, using a series of conservation equations for mass, momentum, and energy transfer, FDS can evaluate over time the dispersion of the battery gas based on the different release scenarios while predicting the time when the detectors would actuate and activate the explosion prevention system, simultaneously deactivating the HVAC cooling system.

Documentation of the model, including validation studies, is readily available (McGrattan et al., NIST Special Publication 1019, sixth edition (FDS Version 6.7.5), August 21, 2020). FDS version 6.7.5 was used for the present work.

2.4. *Approach for the CFD analyses*

A two-step approach is adopted for this work to understand the dispersion and accumulation of battery gas inside the failing stack and the ESS enclosure. The first step (enclosure-level analysis) involves understanding the accumulation of battery gas inside the main enclosure, assuming all of the battery gas released inside a failing stack is directly released into the enclosure atmosphere, which is a conservative hypothesis for the dispersion of battery gas inside the enclosure, as some of the released battery gas may remain inside the failing stack. The second step (stack-level analysis) is to understand the accumulation of battery gas inside an individual stack, assuming some of the battery gas released into the enclosure would eventually re-enter the stack while the HVAC unit operates in the recirculation mode.

Both CFD analyses use the same simulation timeline (Table 3) in which the battery gas disperses in the container and is detected by one of the two hydrogen detectors, and the hydrogen detection results in the activation of the explosion prevention system. In Table 3, (t_1) is estimated during the enclosure-level dispersion analysis, and (t_2) corresponds to the end of the battery release as indicated in Table 2 for the two selected failure scenario events.

Table 3
Simulation Timeline of both CFD Dispersion Analyses.

Event	Event Time (s)
Start of the HVAC system in recirculation mode	−30 s
Start of battery gas release	0
H_2 detection threshold is reached at one of the two H_2 detectors	t_1
Activation of the explosion prevention system	t_1 + 90 s
The explosion prevention system reaches its full capacity after a linear ramp of 20 s	t_1 + 110 s
Battery gas release stops	t_2 seconds

3. Modeling methodology

This section provides an overall modeling methodology for the two corresponding levels of CFD analysis: the enclosure dispersion analysis and the internal Stack 360 dispersion analysis.

3.1. *Modeling setup for the enclosure dispersion analysis*

The CFD model illustrated in Fig. 7 is based on the 3D CAD geometry of the enclosure imported in the software PyroSim developed by Thunderhead Engineering. This model was augmented with point devices to monitor the hydrogen concentration with time. In addition, the HVAC module of FDS was used to set up the HVAC cooling supply and return nodes. At this point, the container had all of its physical features captured that can be used for the CFD analysis. The enclosure material was assumed to be stainless steel of thickness 3 mm. The contents of the enclosure are also assumed to be stainless steel of thickness 3 mm with insulated backing, i.e., no heat loss to the backside boundary.

Each FDS computational cell was a cube of 0.125 feet or 1.5 inches to capture enough detail without a prohibitive computational time. The computational domain was divided into approximately 40 meshes.

Free volume calculations were performed to quantify the amount of space where battery gas can accumulate inside the enclosure. These calculations were performed by assuming all of the obstructions within the enclosure to be solid, including the stacks and the HVAC duct. In that case, the enclosure atmosphere's free volume was 27.3 m^3 (964 ft^3). The dispersion of the battery gas inside the stack with the failing battery is the subject of the internal dispersion analysis detailed in Section 3.2 of this article.

3.2. *Modeling setup for the internal stack dispersion analysis*

The CFD geometry of the half stack with the battery gas release location indicating the failed module is shown in Fig. 8. A 1-cm uniform mesh size was chosen to balance the computational time against resolving the gaps in the battery modules to capture the airflow patterns inside the stack with the failing battery. The resulting free air volume is estimated to be 0.51 m^3 (18.01 ft^3).

4. Modeling results

This section describes the results of the two CFD dispersion analyses used to design the explosion prevention system.

4.1. *Powin Stack™ 360 global dispersion analysis results*

4.1.1. *Battery gas concentration within the enclosure atmosphere*

In this scenario, the battery gas would disperse via entrainment by the HVAC system flow. For each of the two selected failure scenarios, a two-step simulation strategy was used to analyze the different failure scenarios with the HVAC system ON configuration.

Step 1. A CFD simulation was performed to evaluate H_2 detection times. These times were evaluated to occur at 44 s after the start of the single-module failure scenario and at 37 s after the start of the two-module failure scenario,

Step 2. A CFD simulation was then performed, with the activation of

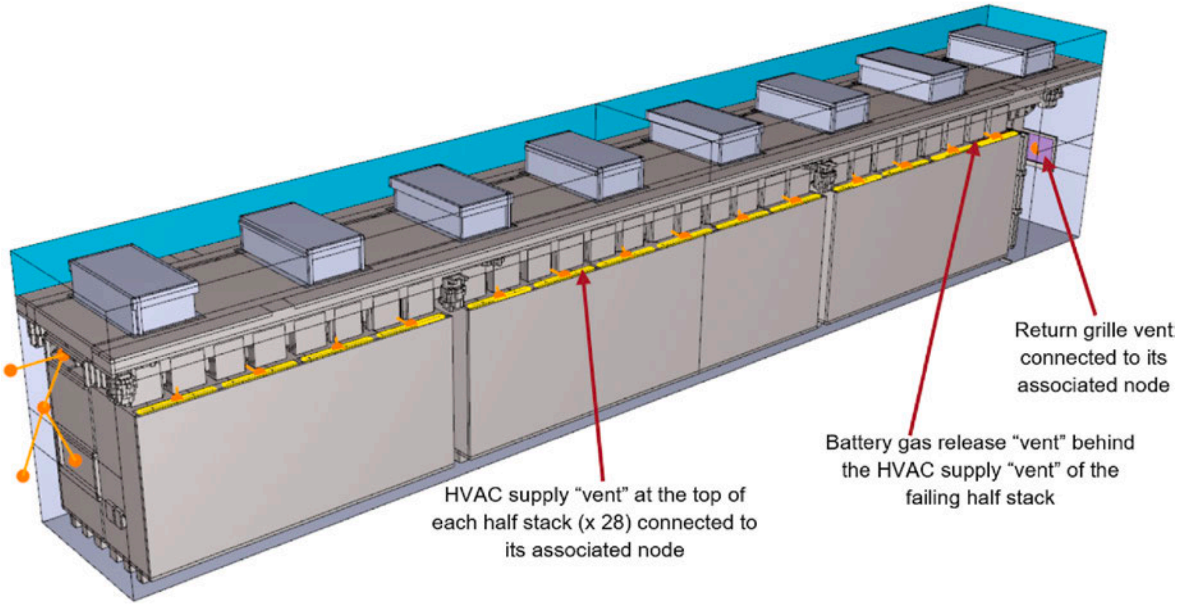


Fig. 7. FDS HVAC components of the Powin Stack™ 360 enclosure.

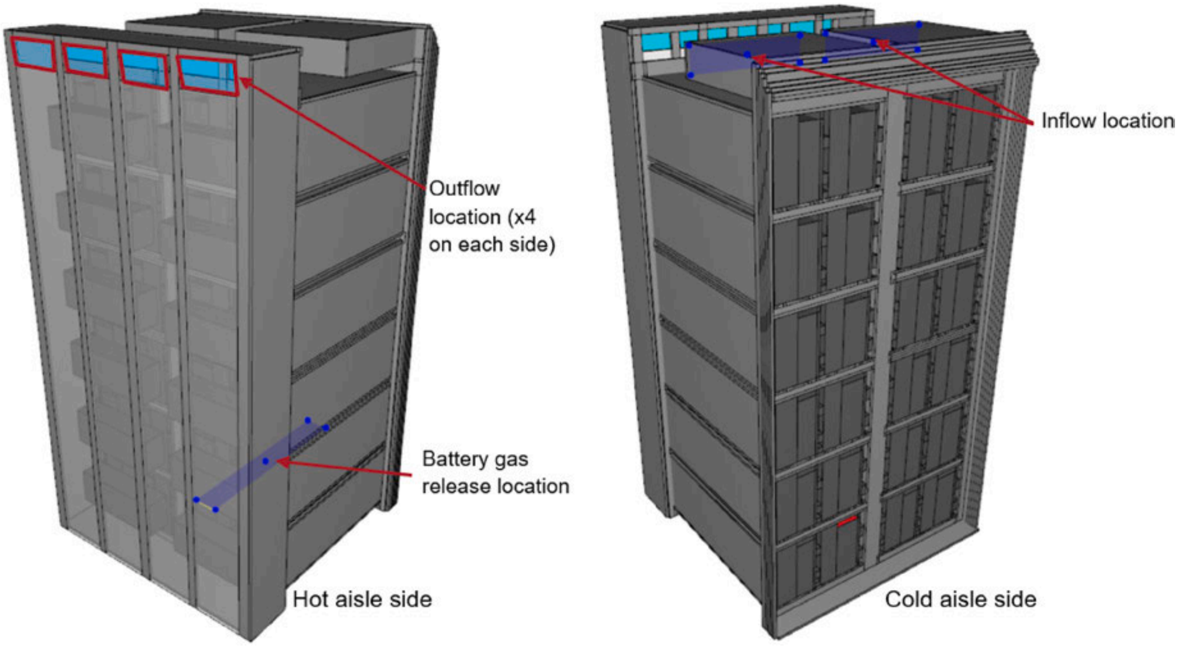


Fig. 8. *Inflow and outflow vent configuration in the CFD geometry for the internal stack dispersion analysis.*

the explosion prevention system 90 s after the detection times estimated in Step 1 increased by a safety factor of 20%.

Fig. 9 shows the global battery gas volume fraction for the two failure scenarios (Step 2), with the maximum estimated at 1.09% or 17.8% LFL for the single-module failure scenario and 0.94% or 15.4% LFL for the two-module failure scenario. These results indicate that the global battery gas volume fraction would remain below the threshold criterion of 25% LFL.

Fig. 9 also shows that before the activation of the ventilation system, the time evolution of the battery gas volume fraction is linear, as the battery release is constant and occurs within an enclosed domain with 100% recirculation.

After detection, the battery gas volume fraction decreases as the explosion prevention system discharges some of the battery gas outside the container. As long as the battery gas release continues, there is an equilibrium between this source of battery gas and its depletion by the explosion prevention system. When the battery release ends, the battery gas concentration within the ESS enclosure generally falls to zero within a minute for the two considered failure scenarios.

Fig. 10 illustrates the evolutions of the battery gas mass in the container over time for the CFD analysis failure scenarios. These evolutions follow the same trend as the battery gas global volume fraction, as illustrated in Fig. 9.

The evolution of battery gas dispersion from its release location to the adjacent control room and the rest of the enclosure is shown in Fig. 11 for various times of the two-module failure scenario. The battery gas volume fraction immediately decreases well below 25% of its LFL after the activation of the explosion prevention system, as shown in

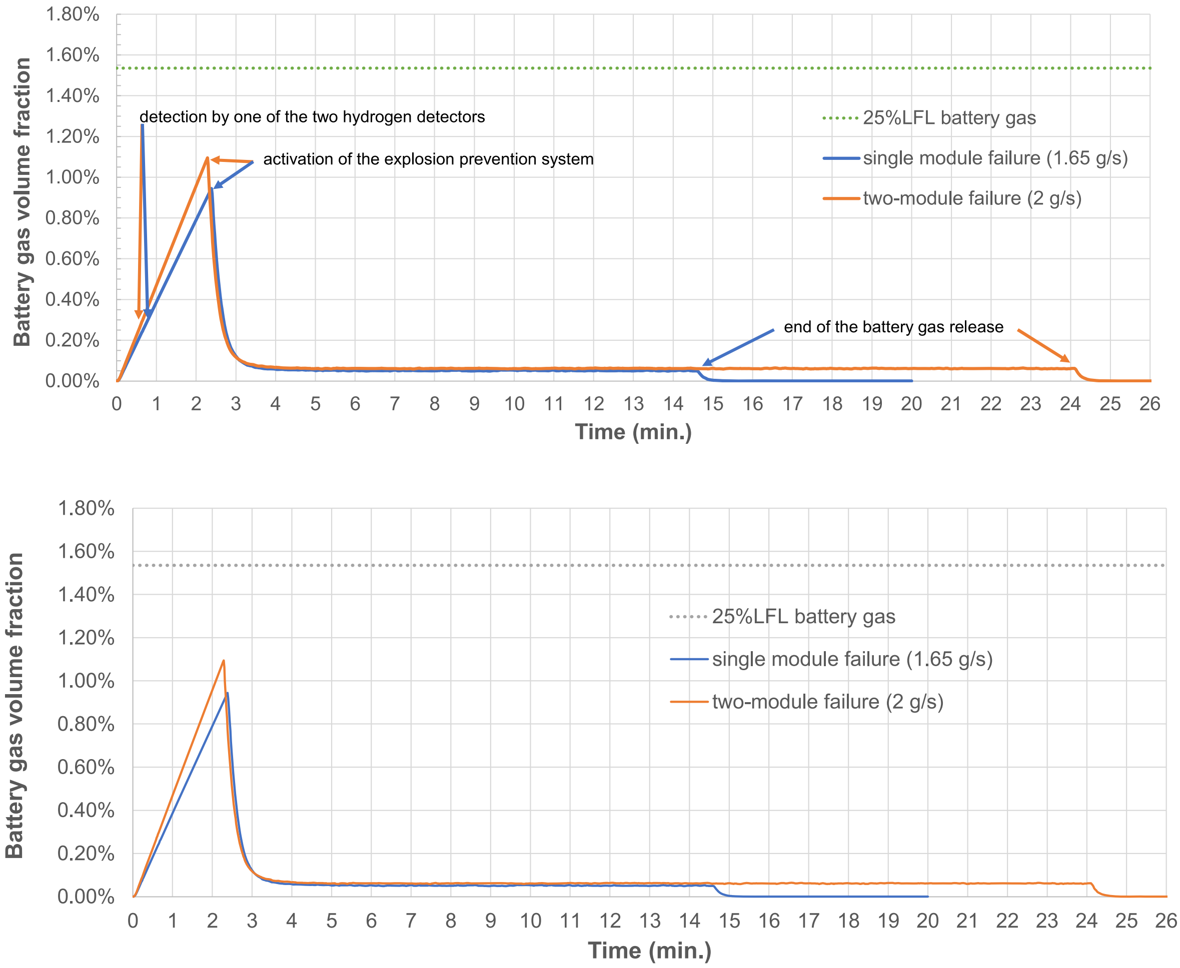


Fig. 9. Evolutions over time of the global battery gas volume fraction for the two considered failure events.

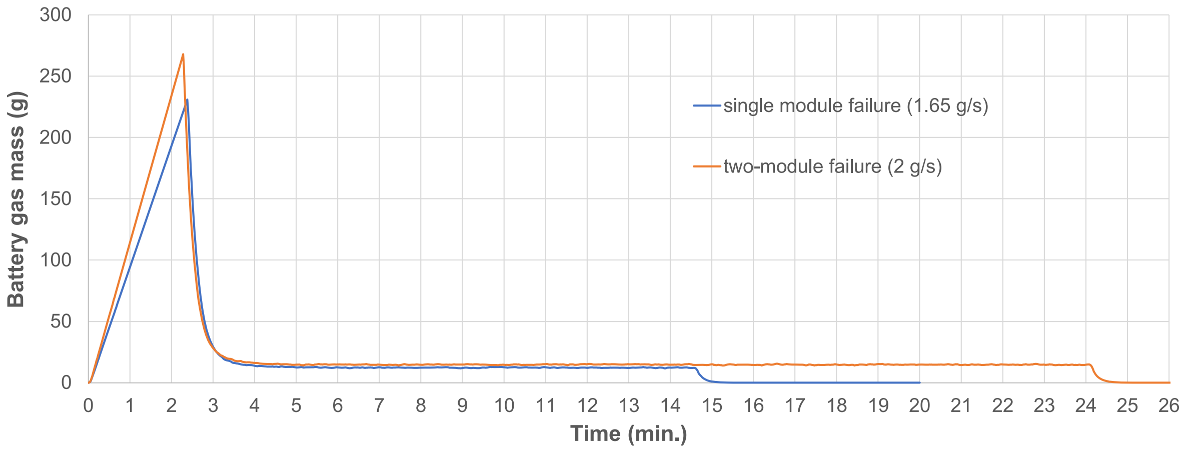


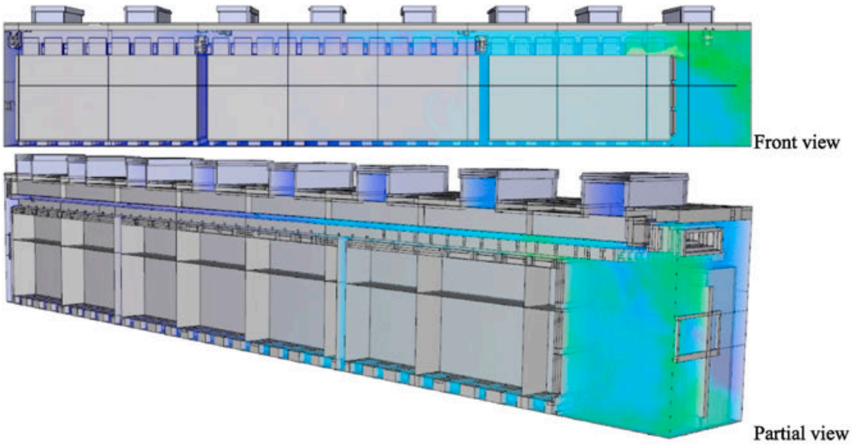
Fig. 10. Evolutions over time of the global battery gas mass for the two considered failure events.

Fig. 11 at 3 min. Note that the local concentrations at the release location can be higher than LFL.

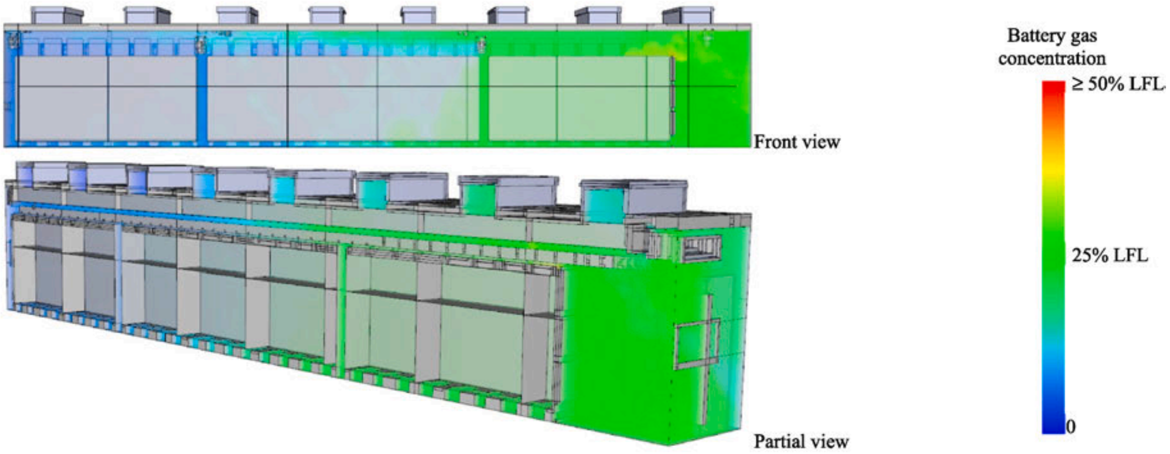
4.1.2. Estimation of the recirculating air contamination with battery gas

The CFD simulations at the enclosure level were also used to determine the contamination of the recirculating air as it flows through the HVAC system. The battery gas contaminates the recirculating air before the explosion prevention system is activated. Based on the CFD model illustrated in Fig. 7, it is possible to estimate the battery gas mass flow rate re-injected into the failing half stack as a portion of the recirculating air increasingly becomes contaminated by battery gas before activation of the explosion prevention system.

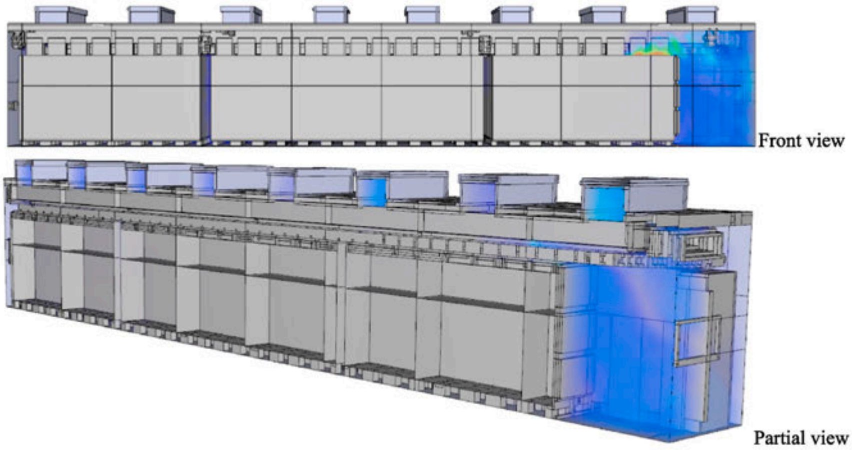
Fig. 12 shows that before the activation of the explosion prevention system, the battery gas mass flow that is re-injected into the failing half stack increases to approximately 5 g/s for the single-module failure event and 5.8 g/s for the two-module failure event. This result can be explained by the fact that the failing half stack is located near the control room, where battery gas tends to accumulate, as illustrated in Fig. 11. A



a) **1 minute after the start of the failure event**



b) **2 minutes and 17 seconds (137 seconds, just prior to activation of the explosion prevention system)**



c) **3 minutes (43 seconds after activation of the explosion prevention system)**

Fig. 11. Battery gas 3D profiles for the two-module failure event.

total of 800 CFM (0.38 m^3/s) or approximately 450 g/s of contaminated air passes through the failing half stack. The CFD simulations showed that the battery gas volume fraction at the right HVAC return grille would increase to approximately 1.7% (26.6% LFL), corresponding to a battery gas mass fraction of 1.3%. A simple calculation of the battery gas returning to the failing half stack based on the total mass flow and battery fraction ($450 \times 0.013 = 5.85$ g/s) at the right return grille validates the results presented in Fig. 12. Note that the other 13 stacks would also encounter the air contaminated with battery gas entering through the stack fans during the recirculation mode. But it is crucial to quantify the battery gas entering through stack fans for the failing stack, as this will augment the total amount of battery gas that can accumulate inside the stack. This information is used as an input for the stack-level analysis, presented in the next section.

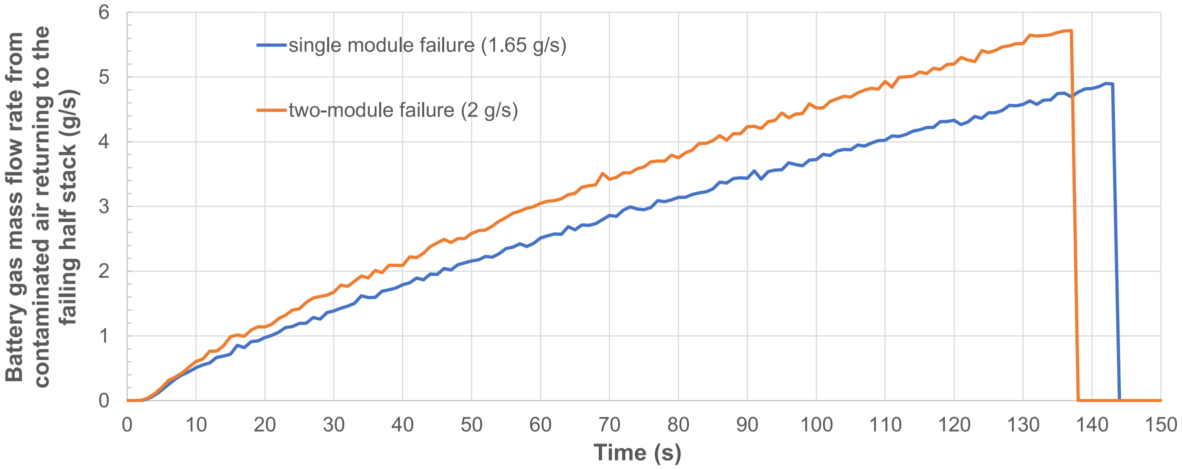


Fig. 12. Rates of battery gas returning to the failing half stack for the two considered failure scenarios.

4.2. *Internal stack 360 dispersion analysis results*

CFD analysis of the Powin Stack™ 360 internal dispersion analysis is performed by considering the battery gas release to occur from a module close to the bottom of the half stack, which is a conservative assumption since the resulting released battery gas would have to disperse through the height of the stack to be ejected outside the stack into the enclosure atmosphere. Variation of the battery gas mass inside the failing half stack cabinet is plotted in Fig. 13. The global battery gas concentration variation within the half stack cabinet is plotted in Fig. 14. The battery gas global statistics within the half stack increase until the explosion prevention system is activated, and clean air is then sent to the stack instead of the recirculating container air, which was becoming contaminated by battery gas, as shown in Fig. 12.

The residual mass of the battery gas within the stack increases up to 8.1 g for the single-module failure event and 9.75 g for the two-module failure event. These values drop to approximately 2 g after the explosion prevention system has been activated. The global concentration of the battery gas inside the failing half stack cabinet is above the 25% LFL limit for less than 1 min before the explosion prevention system is activated for both failure scenarios. The battery gas global concentration drops to 8% LFL during the steady operation of the explosion prevention system. Stack fans being active throughout the release of the battery gas ensure the global concentration within the stack cabinet remains low.

Contours of the battery gas vapor cloud colored by concentration are shown in Fig. 15 for the two considered failure scenarios just before the explosion prevention system is activated. The figure shows the battery gas vapor cloud contours at the following locations.

- on the cold aisle side through which the inflow air is directed,
- on the hot aisle side from where the battery gas is exhausted out of the stack, and
- from a side-view between the stacked battery packs.

Fig. 16 shows the total battery gas emission (source and inlet) compared to the total battery gas exhausted for the half stack for a single-module failure scenario. The same information is provided in Fig. 17 for the two-module failure scenario. These figures indicate that the stack-level dispersion study is compatible with the container-level study presented in the previous section of this report. A low accumulation of battery gas in the failing half stack (Fig. 13) would marginally lower the mass flow rate at the exhaust points and will lead to.

- increase in the detection time for the hydrogen detectors in the container atmosphere (already considered at a 20% higher value for the container level),
- decrease in the global battery gas volume fraction inside the container (leading to a conservative container dispersion level study).

5. Conclusion

A CFD study was performed for the Powin 53-ft ESS enclosure to assess the capability of the explosion prevention system to maintain the

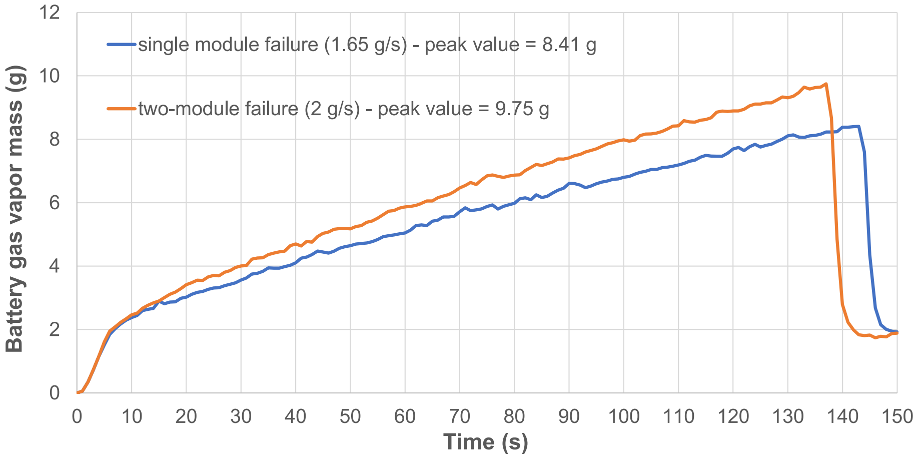


Fig. 13. Variation of battery gas mass inside the failing half Stack 360 cabinet.

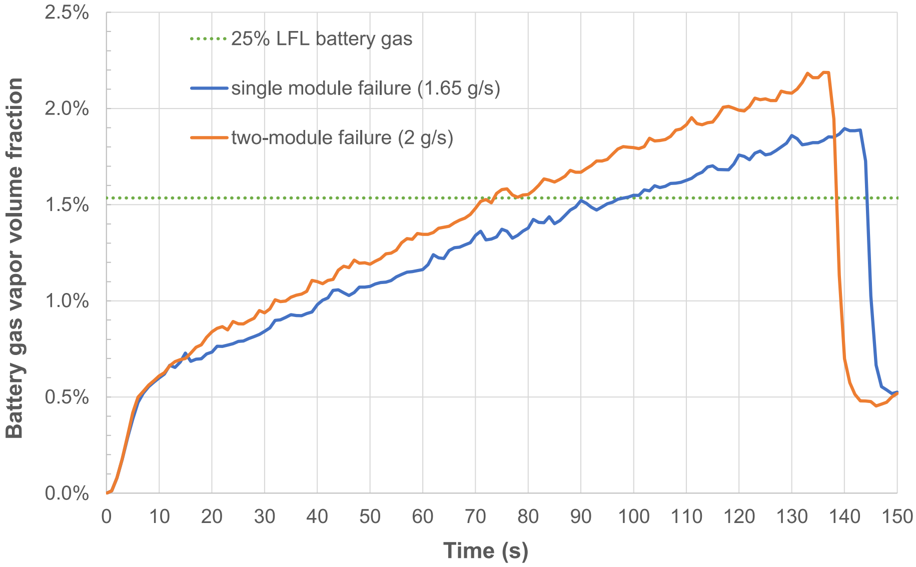
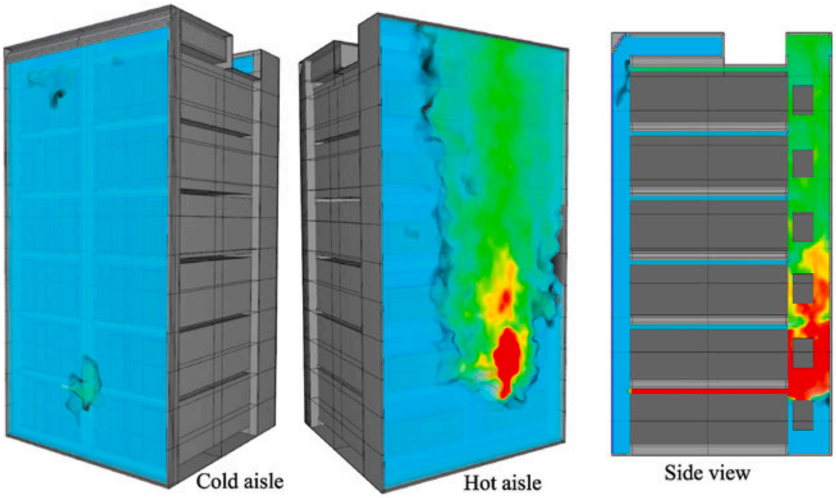
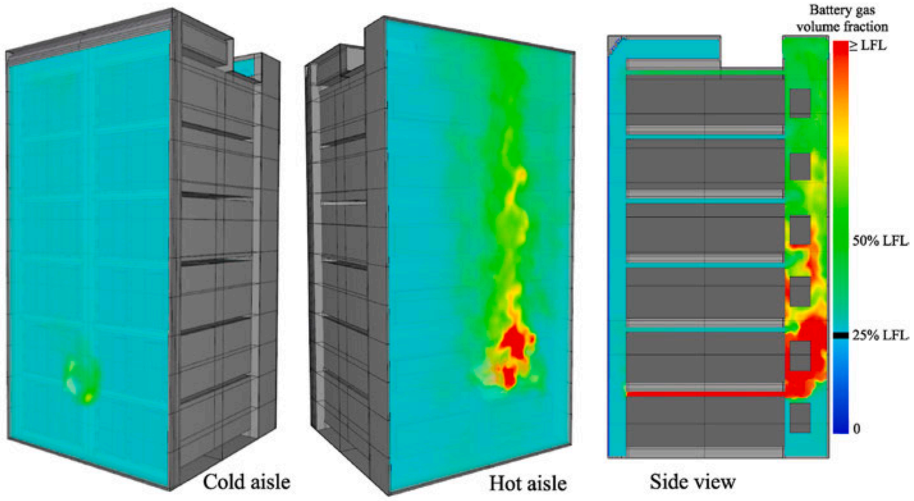


Fig. 14. Variation of battery gas global concentration inside the failing half Powin Stack™ 360 cabinet.



Single-module failure (1.65 g/s), at 140 seconds after the start of the battery release



Two-module failure (2 g/s), at 135 seconds after the start of the battery release

Fig. 15. Battery gas concentration contours during explosion prevention system steady-state operation.

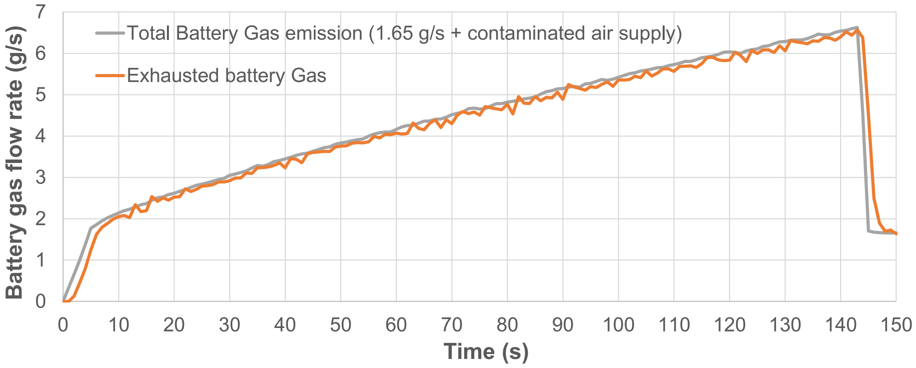


Fig. 16. Evolutions over time of the battery gas sources and release out of the failing half stack for the single-module failure event.

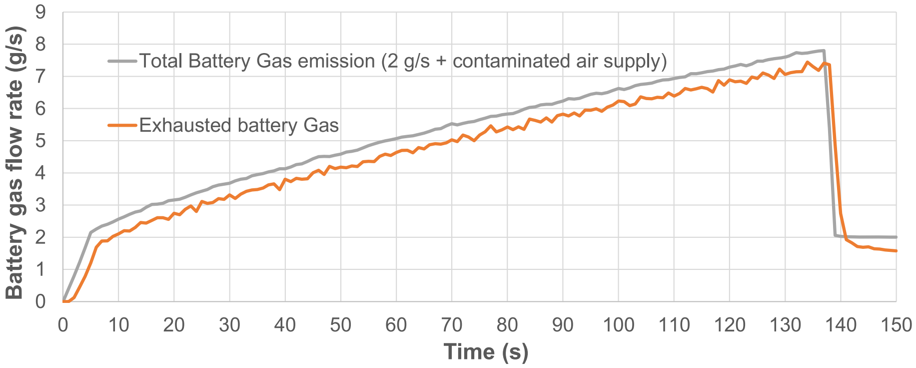


Fig. 17. Evolutions over time of the battery gas sources and release out of the failing half stack for the two-module failure event.

global battery gas volume fraction lower than 25% of its LFL. The explosion prevention system of the Powin Stack™ 360 ESS enclosure utilizes the HVAC system that is switched to its economizer mode (allowing clean air to enter the enclosure and battery gas and air mixture to exit the enclosure) from its recirculating mode.

Two credible failure scenarios based on UL 9540A data were simulated to assess the ventilation system's performance (single- and two-module failure). The analysis was performed at an enclosure level and a stack level using the FDS CFD tool. A gas release model was used as the basis for hazard definition, in accordance with NFPA 855.

The study performed in this work did not consider the activation of a clean agent or an aerosol-based suppression system that may impact the performance of the detection system and the ventilation system. Finally, the explosion prevention system presented here is only limited to the removal of flammable battery gas generated due to the non-flaring decomposition of batteries and is not intended to suppress the growth of an evolving fire or handle a toxic exposure hazard.

The study included two CFD analyses.

- an enclosure-level dispersion analysis to assess the capability of the explosion prevention to maintain the global battery gas volume fraction lower than 25% of its LFL.
- a stack-level dispersion analysis to address the plausibility of developing an explosive environment inside the half stack cabinet while the stack fans operate at 800 CFM (0.38 m^3/s). (In addition, this analysis quantified the influence of battery gas accumulation inside the stack on the container-level analysis.)

The container-level analysis demonstrated the capability of the explosion prevention system to maintain the global battery gas volume fraction inside the container under 25% of its LFL for the two considered failure events. In addition, the analysis assessed the amount of battery gas that would be returning to the failing half stack cabinet while the HVAC system operated in the recirculation mode at the start of the failure events. This estimation was used as an input to the stack-level analysis.

The stack-level analysis was performed to assess the development of an explosive environment inside the half stack cabinet due to the release of battery gas from non-flaring failed battery cells. The half stack itself would cause the released battery gas to accumulate inside the cabinet as it is an enclosed geometry. The stack fans were operating prior to the release of the battery gas in this analysis. This follows the assumption of fans operating if a cell temperature exceeds T_{th}. Note that this is the key assumption for the explosion prevention system to perform successfully.

For the two considered failure events, the internal stack dispersion analysis showed that the peak global volume fraction of the accumulated battery gases inside the stack would be greater than the 25% LFL limit but only for approximately 1 min prior to the activation of the ESS container explosion prevention system. The global battery gas release would reach a steady state of approximately 0.5% vol/vol of air (8% LFL) during the steady-state operation of the explosion prevention system. The explosion prevention system does not prevent local gas concentrations from exceeding the LFL in close proximity to the issuing battery gas or where gases can accumulate. Local spots in the container may have concentrations above the LFL. The evaluated exhaust system significantly reduces the risk of an explosion but does not eliminate an explosion risk.

Overall, the conceptual design assessed in this report meets the intent of NFPA 69 and keeps the global battery gas concentration below 25% of LFL during the steady-state operation for both failure scenarios.

Author contribution statement

Anil Kapahi - Conceptualization, Methodology, Supervision, Writing, review, and editing.Alberto Alvarez-Rodriguez – Formal analysis, Visualization.Sunil Lakshmipathy – Formal analysis, Visualization.

Stefan Kraft - Formal analysis.Jens Conzen- Formal analysis.Angelica Pivarunas – Project Management and Administration.Rody Hardy - Project Management and Administration.Paul Hayes - Project Management and Administration, review.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Anil Kapahi reports financial support was provided by Jensen Hughes Inc.

Data availability

Data will be made available on request.

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Risks related to the Thermal Runaway of Li-Ion Batteries

October 2019

HSE-RM-SPI-REP-2019-047 Rev.2

PSR/HSE/RM/SPI

Revision Management

N° Revision	Date	Authors	Verification	Approval
1	June 2019	D Roosendans (PSR/HSE/RM/SPI) A. Dutertre (PSR/HSE/RM/SPI)		
2	October 2019	D Roosendans (PSR/HSE/RM/SPI) A. Dutertre (PSR/HSE/RM/SPI)		

Executive Summary

Battery packs and modules have been used extensively in industries such as consumer products, transportation, telecommunications and grid energy storage. In recent years, the trend has been to use higher capacity batteries or packs, allowing the user to store more energy, to extract it at a higher rate, and to extend the application to new fields such as smart grid and off-grid storage. However, understanding the safety aspects of these large battery systems and managing failures in higher energy cells such as lithium-ion batteries is a growing concern for many industries.

One of the most catastrophic failures of a lithium-ion battery system is a cascading thermal runaway event where multiple cells in a battery fail due to a failure starting at one individual cell. Thermal runaway can occur due to exposure to excessive temperatures, external shorts due to faulty wiring, or internal shorts due to cell defects. Thermal runaway events result in the venting of toxic and highly flammable gases and the release of significant energy in the form of heat. If ignited, these gases can cause enclosed areas to over pressurize, and if unmitigated, this overpressure can result in an explosion and severe damage to the battery and surrounding equipment or people.

In this study, a characterization was undertaken of the reactivity and flammability of gases discharged during thermal runaway of Li-Ion batteries provided by SAFT. Based on this characterization, a credible worst case scenario was developed for generation and accumulation of flammable gases in a container upon thermal runaway. Finally, gas explosion risks were quantified and assessed, together with the discussion of possible mitigating measures. Fire and toxic risks upon discharge of gases outside the battery container are also addressed in this study.

Simulation results indicate that see that the Lower Explosion Limit and the flammability range of gases discharged during thermal runaway of SAFT Li-Ion pouch cells are higher than those of typical hydrocarbons but lower than for carbon monoxide and hydrogen. The simulation results also show that the laminar burning velocity of the gases discharged during thermal runaway of SAFT Li-Ion pouch cells is comparable to that of methane and far below the laminar burning velocity of hydrogen.

For management of the explosion risk of flammable gases in the 35 m^3 container during thermal runaway of the 320 Li-Ion pouch cells in a battery rack (considered to be a credible worst case scenario), the following preventive and consequence mitigating strategies are possible.

- Dilution of the generated flammable gas below LEL by external ventilation of the container;
- Inerting of the flammable mixture in the container by injection of inert gas (CO_2);
- Limitation of overpressure in the container (in case of ignition of the flammable gas) by explosion relief panels.

Preliminary ventilation calculations using varying flammable gas discharge rates indicate that the atmosphere in the battery container can be kept below the Lower Explosion Limit if an external ventilation rate of minimum 400 Nm^3/h is maintained in the container during the thermal runaway event. If more detailed results about the impact of external ventilation of the container are required, than a 3D simulation using the exact geometry and layout of the battery container and ventilation system needs to be performed.

Upon use of a fire extinguishment system (based on inert gas injection), calculations show that that about 30 vol% of CO_2 needs to be added to inert the flammable mixture generated during thermal composition of SAFT Li-Ion pouch cells. These results are in line with the concentrations of CO_2 required to inert methane/air and propane/air flames.

Upon use of blast relief panels to mitigate the effects of an internal explosion in the container, the total surface of these blast panels needs to be large enough for effective mitigation of the blast. Based on a preliminaray evaluation using literature data, this total surface must be minimum 40 to 60% of the total surface of the container roof to be effective. The application of a recently developed engineering model for evaluation of the peak pressure in vented explosions of hydrogen and hydrocarbons suggests that the battery container can be adequately protected by installing six 24”x36” blast panels in the roof of the container.

The effect of heat radiation and toxic gas dispersion upon venting into ambient atmosphere of the gases generated during thermal runaway of the batteries in an entire rack was also assessed. Heat radiation calculations and toxic gas dispersion calculations indicate that significant effects on people and assets are limited to the immediate vicinity (meters) from the battery container.

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1 Introduction

1.1 General

Battery packs and modules have been used extensively in industries such as consumer products, transportation, telecommunications and grid energy storage. In recent years, the trend has been to use higher capacity batteries or packs, allowing the user to store more energy, to extract it at a higher rate, and to extend the application to new fields such as smart grid and off-grid storage.

Battery energy storage systems are usually pre-engineered devices, containers or buildings. The “Intensium Max” container is such an energy storage system (ESS) designed by SAFT Batteries (see Figure 1). The current design of the “Intensium Max” container exists out of the following components:

- A standard 20 feet steel plated container to contain the ESSU’s;
- A ESSU consists of a steel cabinet containing the battery modules;
- 18 ESSU’s with 15 battery modules of 28 cells each inside;
- HVAC system for temperature and air control;
- An inert gas extinguishing system in case of fire;
- A distribution cabinet for power distribution and battery management.

The module housing is made from plastic with a flame-retardant separation between the cells. The cells are Lithium-Ion cells with a thermal runaway temperature between 120°C and 140°C

Figure 1 Inside of Intensium Max Container by SAFT

The understanding the safety aspects of these large battery systems and managing failures in higher energy cells such as lithium-ion batteries is a growing concern for many industries.

1.2 Thermal Runaway of Li-Ion Batteries

One of the most catastrophic failures of a lithium-ion battery system is a cascading thermal runaway event where multiple cells in a battery fail due to a failure starting at one individual cell. Thermal runaway can occur due to exposure to excessive temperatures, external shorts due to faulty wiring, or internal shorts due to cell defects.

Thermal runaway events result in the venting of toxic and highly flammable gases and the release of significant energy in the form of heat. If ignited, these gases can cause enclosed areas to over pressurize, and if unmitigated, this overpressure can result in an explosion and severe damage to the battery and surrounding equipment or people. An explosion scenario can be even more severe for a large battery pack, where the heat generated by one failed cells can heat up neighboring cells and lead to a thermal cascade throughout the battery pack. Understanding the reasons for thermal runaway and the consequences of such an event is helpful for purposes of avoiding or planning for cell failures. Thermal failures of batteries make news headlines, whether in the transportation industry or others.

Several incidents happened in the past. In November 2017, a 1 MW battery container supplied by Engie Ineo at the power plant of Drogenbos (Belgium) caught fire. This fire was long-lasting fire with full loss of the unit as a result even with an intervention of the fire department

Figure 2 Fire of a 1MW battery container in Drogenbos (Belgium)

In Hawai, a large-scale Li-Ion ESS (batteries with solid electrolyte) caught fire at the Kahuhu windfarm. The fire department refused any intervention because of the toxic gasses produced by the burning batteries, with a total loss of the unit as a result.

Figure 3 Example of an ESS that caught fire on the Kahuhu windfarm

In the United States, some incidents related to ESS have been reported:

- A fire of an ESS container occurred in Arizona in November 2012. Little is known about actual causes and how the fire spread, but it originated within the ESS containers. The root cause however is unknown.
- Another fire of an ESS container happened in Wisconsin in August 2016. While the fire started around the batteries, they themselves were not the cause. They did however contribute to the size of the incident.
- A Li-Ion ESS container exploded in Arizona on April 2019. This event, at a substation of power utility Arizona Public Service, injured eight fire fighters, four of whom were hospitalized for evaluation.

In April 2017, a container filled with Li-on consumer batteries transported via rail (Union Pacific 53' double stacked rail car) exploded. The batteries were on its way to a recycling facility. The explosion broke windows of buildings at a distance of about 150 meters.

Figure 4 Explosion of container filled with consumer Li-Ion batteries during rail transport

In South Korea, 23 incidents have occurred in different ESS since August 2017. The large number has to be put in some perspective as in 2018, half of the world's ESS facilities were located in South Korea (5.6 GWh of. 11.6 GWh). The incidents took place in facilities of three independent ESS suppliers. In the beginning of 2019, the government has asked to stop using ESS. Approximately 35% of the ESS have been shut down. The incidents have been investigated by a committee appointed by the South Korean government. They have identified 4 main causes:

- Faulty battery protection systems that protect insufficiently against electric shocks;
- Improper operation management;
- Faulty installation of systems;
- Lack of an overall control unit;

While some battery defects were found, none of these were sufficiently serious to recreate a fire. Most of these causes are associated with a very fast growth in ESS systems without enough regulatory controls. With the emergence of new standards (such as NFPA 855), the amount of incidents in new installations should reduce.

1.2.1 Single Cell Failure

Thermal runaway occurs when the temperature of a cell increases in an uncontrolled manner, leading to its failure. This temperature increase generates gases, which vent when the pressure inside the cell rises above a design value. For lithium-ion cells, these gases are hot and combustible, which can become a hazard if a pack was not designed to control the causes and consequences of thermal runaway.

All thermal runaway events are a result of a rise in cell temperature. This temperature rise can have multiple causes, including, but not limited to:

- The use of cells in high temperature environment.
- A defect inside the cell can result in an internal short circuit, which causes the cell to heat up at the location of the defect.
- A surge in the charging or discharging current. When cells are charged or discharged, heat is generated. The higher the current, the higher the heat generation.
- An improper electrical connection at the tab of a battery. This causes an increased electrical resistance which generates heat at the electrical contacts.
- Mechanical damage to the cell or battery which can also lead to internal shorts and result in heat generation.

Cells generate heat, even under normal operating conditions. The heat generation from charging and discharging cycles are not expected to induce a thermal runaway event unless this heat is allowed to accumulate and slowly heat up the cells and the battery to a point where irreversible changes to the cell and failures may occur. However, if the cell develops an internal short due to manufacturing defects, mechanical abuse or external heating, the heat generated from the cell may be large enough to initiate a thermal runway event.

In addition, exothermic chemical reactions occur within the cell even if the cells are not in use. As the temperature increases, the self-heating rate also increases. At approximately 130°C, the self-heating rate increases dramatically. The exothermic reactions are negligible at low temperatures, but become significant as the cell temperature increases. At higher temperatures, the cell short-circuits. Gases build up within the cell and eventually vent.

1.2.2 Discharged Gases during Thermal Runaway of Li-Ion Batteries

During a thermal runaway event, the cell produces gases that build up within the cell. Some cell designs include a specially designed vent that opens, and releases the gases. In some cases, this vent can become obstructed or may not open correctly, which may result in rupturing of the cell enclosure. Other cell form factors, such as pouch cells, do not include a specific vent and the gases will release at weak points in the external pouch, typically near the tabs of the cell or along the pouch seams in unconstrained cells. The release of vented gases avoids the catastrophic failure of the cell containment structure, but it creates a new hazard associated with the flammability of the vented products if ignition occurs.

In case of a thermal runaway, the composition of the gases is different depending whether cells combust during failure as opposed to simply going into thermal runaway and venting. Thermal runaway does not always lead to combustion and the differences in thermal runaway temperatures and combustion (and hence gas generation) may be of the order of 400 to 500°C (about 350 to 400°C without combustion and 750-850°C with combustion). The states of charge (SOC) of the batteries and their energy capacity tend to determine likelihood of combustion, can lead to a range of results based on numerous factors.

If the flammable gases produced during thermal runaway are ignited in a confined environment, they can present overpressurization and explosion hazard. This is particularly true for large battery packs, where the battery modules are often contained in an enclosure. An explosion can occur when the uncombusted vented gases mix with remaining air in the enclosure or with fresh air that enters the enclosure from vents and openings and the resulting mixture is ignited by either the failing cells or a different ignition source in the enclosure.

1.2.3 Propagation of Failure, Hazards and Prevention

Thermal runaway events can result from uncontrolled increases in cell temperature. During the failure process, the cell self-heats and combustible gases are vented. In addition, these vented gases, as well as the battery itself can ignite, generating even more energy released. Thermal runaway is therefore a highly exothermic, self-propagating process. As a result, there is a risk that a failing cell could heat neighboring cells causing a cascading event where thermal failure propagates from cell-to-cell, and battery to battery. Lithium-ion cells are still a relatively new technology and thermal runaway events are not completely understood.

To avoid thermal runaway, and to prevent propagation of the failure from cell to cell, one needs to be able to control the temperature of individual cells or of small groups of neighboring cells. Many potential thermal management systems exist and depending on the application, they can involve fins, fans circulating cooling air, phase changing materials that absorb a significant amount of heat without changing temperature, *etc.* They can also be used in combination with control algorithms that either stop drawing currents if the cell is overheating, or discharge neighboring cells if one cell in the pack is expected to fail.

The design of such a thermal management can be trivial for simple applications, but becomes more complex when more energy is stored, when space is limited, or in harsh environmental conditions. Three-dimensional numerical simulations using Computational Fluid Dynamics (CFD) can provide comparative information of the efficiency of various designs under various failure scenarios. A typical simulation will provide information about temperatures and air flow rates, and is able to detect areas where heat cannot be easily dissipated.

Beyond controlling temperatures, mitigation techniques can be used to limit the consequences of a failure. In particular, vented gases are hot and can even melt metal if the cell vents right next to it. Depending on the application, a review of the design for purposes of assessing the risk associated with the fate of the vented gases injuries may involve a simple review of the pack layouts, or could require tests or full numerical analysis of the fate of the gases in complex geometries.

Failing cells generate a relatively large quantity of gases at high temperatures. If the cells are enclosed in a casing, the pressure inside the casing can increase either because of overpressurization or explosion due to combustion of the vented gases. Casings can be designed to be able to contain such a pressure rise, or can include vents that open when the pressure rises above a predetermined threshold. Such vents are commonly used in many industries to mitigate the risks of explosions. NFPA 68 provides guidance for the design of vents to prevent high overpressures in enclosures. The ability to quantify both the maximum overpressure and the explosion index allows for direct application of NFPA 68 to battery systems. Similarly, NFPA 497 can be used to prevent flame propagation by using flame arresters.

2 Scope of Study

The proposed scope of this study includes the following aspects:

- Characterization of the reactivity and flammability of gases liberated during thermal runaway of Li-Ion batteries.
- Specification of a credible worst case scenario for generation and accumulation of flammable gases in a container upon thermal runaway.
- Evaluation of gas explosion risks and specification of possible mitigating measures.
- Evaluation of heat radiation risks upon discharge of flammable gases outside the battery container.
- Evaluation of toxic risks upon discharge of gases outside the battery container.

3 Characterization of Gases Discharged during Thermal Runaway

A detailed study on the characterization of gases that are discharged during thermal runaway of Li-Ion batteries can be found in Appendix I. A summary of the characteristics of the flammable gases generated during thermal composition of SAFT Li-Ion pouch cells is given in Table 1. The values for lower and upper explosion limit were derived from the assumption that flames with laminar combustion velocities lower than 0.05 m/s are unable to propagate. The spread in values for maximum laminar burning velocity, LEL, UEL and maximum adiabatic flame temperature come from the application of 2 different kinetic models in the calculation.

Table 1 Characteristics of flammable gases generated during thermal runaway of SAFT Li-Ion pouch cells

Parameter	Value
Maximum laminar burning velocity (m/s)	≈ 0.31-0.36
Lower explosion limit (vol%)	≈ 13.3-15.4
Upper explosion limit (vol%)	≈ 37.5-42.5
Maximum adiabatic flame temperature (K)	≈ 2080-2110

An overview of explosion limits for some flammable gases are given in Table 2. One can see that the Lower Explosion Limit and the flammability range of gases discharged during thermal runaway of SAFT Li-Ion pouch cells are higher than those of typical hydrocarbons but lower than for carbon monoxide and hydrogen.

The higher values for the Lower Explosion Limit found for the flammable gases from a discharge of SAFT pouch cells (compared to the LEL for Li-Ion pouch cells found by Somandepalli et al.) can be explained by the significantly lower concentration of hydrogen and the higher concentration of carbon dioxide in discharged gases by SAFT pouch cells (see also Table 4).

Table 2 Explosion limits of various flammable gases

Gas	LEL (vol%)[1]	UEL (vol%)[1]
Flammable gases from thermal runaway of SAFT pouch cell	13.3 -15.4	37.5-42.5
Flammable gases from thermal runaway of 7.7 Wh pouch cell at SOC of 50% tested by Somandepalli et al (2014)	6	≈ 38
Flammable gases from thermal runaway of 7.7 Wh pouch cell at SOC of 100% tested by Somandepalli et al (2014)	6	40
Carbon monoxide	12.5	74.0
Hydrogen	4.0	75.0
Methane	5.0	15.0
Ethylene	2.7	36.0
Acetylene	2.5	100.0
Ethane	3.0	12.4
Propylene	2.4	11.0
Propane	2.1	9.5
isoButane	1.8	8.4
n-Butane	1.8	8.4
Butene	1.6	10.0
Pentane	1.4	7.8
Hexane	1.2	7.4

[1] Data extracted from Gas Data Book, 7th edition, copyright 2001 by Matheson Gas Products, and from Bulletin 627, Flammability Characteristics of Combustible Gases and Vapors, copyright 1965 by U.S. Department of the Interior, Bureau of Mines.

An overview of laminar burning velocities of some flammable gases are given in Table 3. The simulation results indicate that the laminar burning velocity of the gases discharged during thermal runaway of SAFT Li-Ion pouch cells is comparable to that of methane and far below the laminar burning velocity of hydrogen. The lower values for the laminar burning velocity found for the flammable gases from a discharge of SAFT pouch cells (compared to the laminar burning velocities for Li-Ion pouch cells found by Archibald and Marr (2018) and the laminar burning velocities for Li-Ion batteries found by Johnsplass et al.) can be explained by the significantly lower concentration of hydrogen and the higher concentration of carbon dioxide in discharged gases by SAFT pouch cells (see also Table 4).

Table 3 Laminar burning velocities for various flammable gases

Gas	Equivalence Ratio	Laminar Burning Velocity (m/s)
Flammable gases from thermal runaway of SAFT pouch cel[1]	≈ 1.10	≈ 0.31-0.36
Flammable gases from thermal runaway of 7.7 Wh pouch cell at SOC of 50% tested by Somandepalli et al (2014)[2]	≈ 1.10	≈ 0.48
Flammable gases from thermal runaway of 7.7 Wh pouch cell at SOC of 100% tested by Somandepalli et al (2014)[2]	≈ 1.14	≈ 0.48
Flammable gases from thermal runaway of 7.7 Wh pouch cell at SOC of 150% tested by Somandepalli et al (2014)[2]	≈ 1.17	≈ 0.64
Flammable gases from thermal runaway of LCO Li-Ion battery tested by Golubkov et al. (2014)[3]	≈ 1.21	≈ 0.66
Flammable gases from thermal runaway of LNMCO Li-Ion battery tested by Golubkov et al. (2014)[3]	≈ 1.13	≈ 0.50
Flammable gases from thermal runaway of LFP Li-Ion battery tested by Golubkov et al. (2014)[3]	≈ 1.06	≈ 0.37
Hydrogen[4]	1.00	2.17
Methane[4]	1.00	0.36
Ethylene[4]	1.00	0.63
Acetylene[4]	1.00	1.25
Ethane[4]	1.00	0.44
Propylene[4]	1.00	0.39
Propane[4]	1.00	0.39
isoButane[4]	1.00	0.32
n-Butane[4]	1.00	0.39
Butene[4]	1.00	0.42

1: From simulations performed in the context of this study, using the GRI-Mech 3.0 reaction mechanism and the kinetic model published by Wang et al. (2007).
2 From simulations performed by Archibald and Marr (2018)
3 From simulations performed by Johnsplass et al.
4 From simulations performed in the context of this study, using the kinetic model published by Wang et al. (2007)

Table 4 Comparison of composition of flammable gases discharged during tests with Li-Ion batteries

	Somandepalli et al. (2014)			Golubkov et al (2014)			Arora et al. (2018)[1]
	SoC 50%	SoC 100%	SoC 150%	LNMCO	LCO	LFP	SAFT
CO_2	32.3	30.0	20.9	41.3	25.0	52.0	42.5
CO	3.61	22.9	24.5	13.1	27.7	4.8	29.4
H_2	31.0	27.7	29.7	30.2	30.1	31.0	14.73
CH_4	5.78	6.39	8.21	6.9	8.6	4.1	7.31
C_2H_4	5.57	2.19	10.8	8.3	7.8	6.9	2.93
C_2H_6	2.75	1.16	1.32	0.0	1.2	0.3	0.55
C_3H_6	8.16	4.52	0.013				0.37
C_3H_8	0.68	0.26	2.54				0.92
iC_4H_{10}	0.41	0.20	0.13				0.28
C_4H_{10}	0.67	0.56	0.39				0.10
C_4H_8	2.55	1.58	0.60				0.11

1: average value from 3 tests using 3 identical pouch cells

4 Credible Worst Case Scenario Definition

The specification of a credible scenario is required for assessment of the explosion and fire risk of flammable gases in the 35 m^3 container (with a free volume of about 18 m^3). As a credible worst case scenario, the thermal runaway of all batteries in a single battery rack in the container was assumed. A single battery rack consists of a number of battery modules. Every battery module contains 20 to 30 Li-Ion pouch cells. The total number of Li-Ion pouch cells in a single battery rack is assumed to be 320.

A list of parameters describing the credible worst case scenario can be found in Table 5.

Table 5 Explosion Scenario Definition

Parameter	Value	Remarks
Geometrical volume of container	34.5	Container dimensions: 6 m x 2.5 m x 2.3 m
Free volume of Container (m^3)	18	
Surface external ventilation opening (m)	0.5	
Flammable gas production per pouch (m^3)	0.0321	Based on testing by Arora et al. (2018)
Number of pouches in a single battery rack (-)	320	A battery rack consists of a number of modules containing about 20 to 30 Li-Ion pouch cells each
Total volume of flammable gas generated during thermal runaway of all batteries in a battery rack (Nm^3)	10.27	
Total time for flammable gas release from all pouches in a battery rack (s)	900	Assumption
Flammable gas production rate during thermal runaway of all batteries in a battery rack (Nm^3/s)	See possible discharge rate profiles in Figure 31 to Figure 36	
Flammable gas density (kg/Nm^3)	1.38	
Lower Explosion Limit of generated gases (vol%)	13.3	Minimum of values for LEL obtained by simulations in Section 3
Upper Explosion Limit of generated gases (vol%)	37.5	Minimum of values for UEL obtained by simulations in Section 3

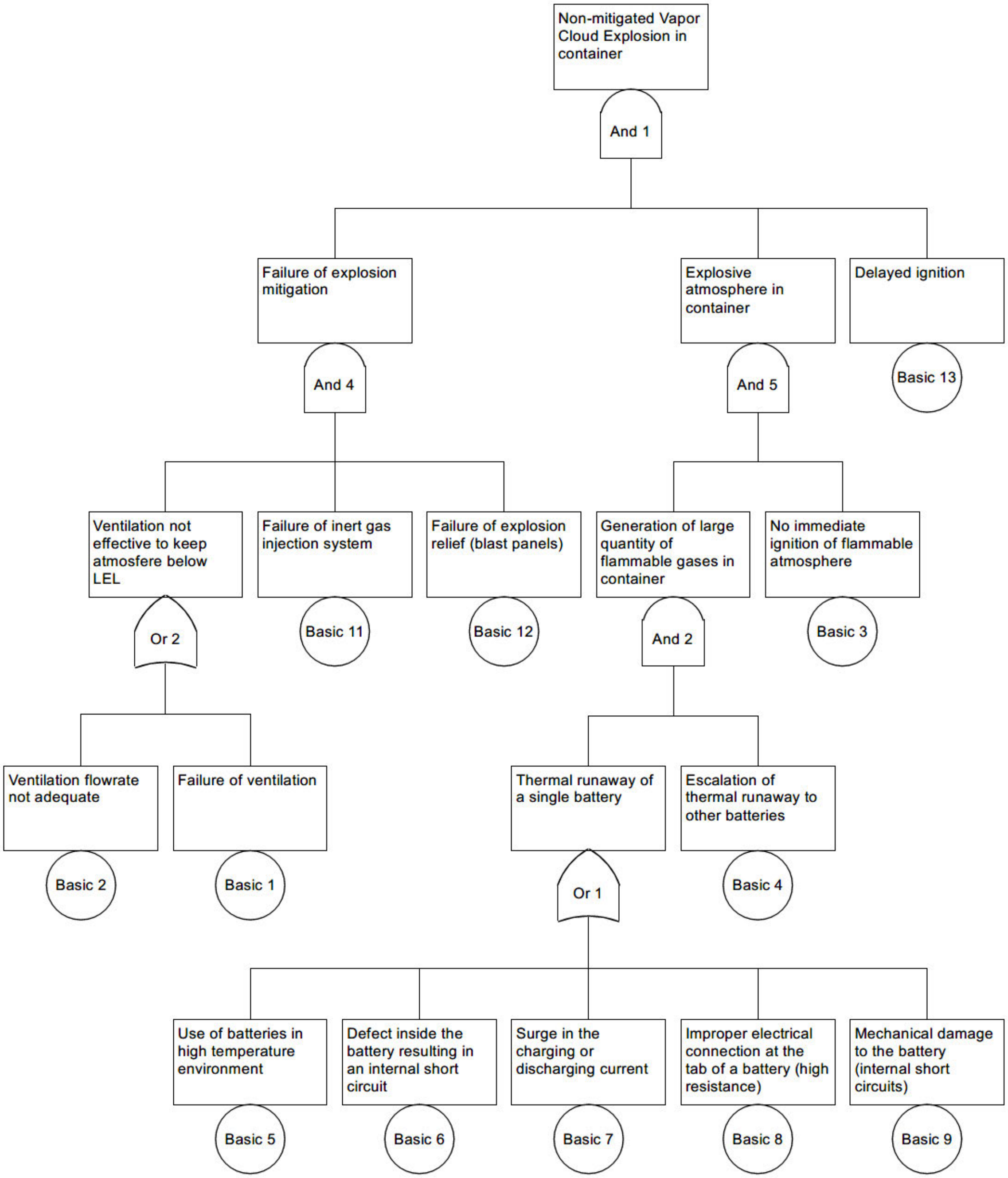
A constant discharge profile was assumed for simulation of heat radiation and toxic gas dispersion upon venting of the gases generated during thermal runaway of the batteries into ambient atmosphere. Varying total discharge times were assumed for these simulations (300 s, 600 s and 900 s).

5 Explosion Risks

5.1 Generic Event Tree

The following simplified generic event tree can be developed for an explosion of flammable gases that accumulate inside the container upon thermal runaway of the Li-Ion batteries.

Figure 5 Generic event tree for creation of a flammable atmosphere inside a battery container



5.2 Explosion Mitigating Barriers

For management of the explosion risk of flammable gases in the 35 m^3 container during thermal runaway of the 320 Li-Ion pouch cells in a battery rack, the following preventive and consequence mitigating strategies are possible.

- Dilution of the generated flammable gas below LEL by external ventilation of the container;
- Dilution of the generated flammable gas below LEL by injection of inert gas (CO_2);
- Limitation of overpressure in the container (in case of ignition of the flammable gas) by application of explosion venting using relief panels.

Both options are studied below.

5.2.1 External Ventilation of the Container

A first approximation of the efficiency of external ventilation can be obtained by use of the concept of a perfectly stirred reactor for calculation of the minimum external ventilation rate of the container to keep the atmosphere inside the container below the Lower Explosion Limit of 13.2 vol%.

Using this concept, the following equation applies for calculation of the concentration of the flammable gas generated during thermal runaway of the Li-Ion batteries:

$$C = \frac{\mathrm{V}_{gas}(\mathrm{t}) \cdot 100}{\mathrm{V}_{container} + \mathrm{Q}_{ventilation} \cdot t}$$

with:

C	concentration of flammable gas in container (vol%)
$V_{gas}(t)$	accumulated volume of gas in container at t due to thermal runaway of batteries (Nm^3)
$Q_{ventilation}$	external ventilation rate in container (Nm^3/s)
$V_{container}$	free volume of container (m^3)
t	time (s)

The parameter values in Table 5 were used for the calculations. Since the exact profile of the flammable gas discharge rate upon thermal runaway of all the batteries is the container is not known, several profiles for this discharge rate were postulated for the calculations. These rate profiles are given in Figure 29 of Appendix II. The total amount of flammable gas discharged for each of the 4 discharge rate profiles is given in Figure 30 of Appendix II.

The results of the calculations for 7 different gas discharge rate profiles are shown in Figure 31 to Figure 35 of Appendix II. To stay below the Lower Explosion Limit of 13.2 vol% for all considered discharge rate profiles, an external ventilation rate of minimum 400 Nm^3/h must be maintained in the container during the thermal runaway event.

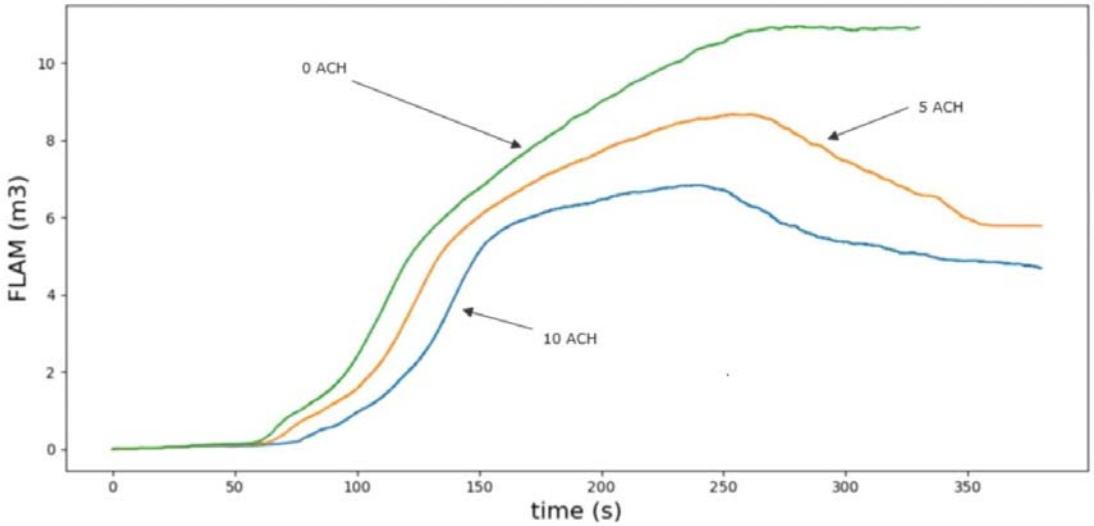
For effective and efficient use of the container ventilation system as a safety barrier, the following measures can be considered:

- External ventilation at nominal rate in case of absence of carbon monoxide (to be measured by local CO detector).
- Increase of external ventilation rate to 400 Nm^3/h (or more) in case of CO detection in the container. The high CO content of the flammable gases generated during thermal runaway of batteries allows a rapid detection based on CO concentration.
- Independent power supply to the external ventilation system (to avoid common mode failures in case of fire in the container).

Note that the external ventilation system will not avoid the start of a fire in case of thermal runaway of one or more of the Li-Ion cell pouches. In case of such a fire, the ventilation system may increase the combustion by introduction of fresh air into the container. Therefore, an adapted strategy needs to be developed to establish when to stop the external ventilation in case of a confirmed fire inside the container and at the same time avoid the creation of an explosive atmosphere inside the container upon extinguishment of the fire.

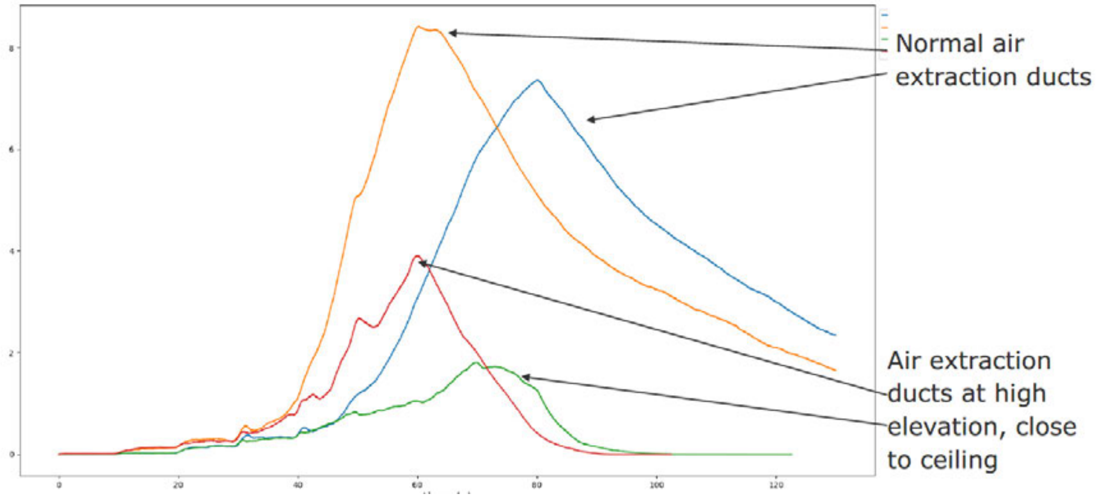
If more detailed results about the impact of ventilation of the container are required, than a 3D simulation using the exact geometry and layout of the battery container and ventilation system needs to be considered. Such an analysis was performed in an ongoing Joint Development Project for battery safety led by DNV GL (Warner et al., 2018). The influence of external ventilation on the flammable cloud volume in a battery container upon thermal runaway of Li-Ion batteries was investigated in this project. Preliminary results from CFD simulations demonstrate the effect that increased ventilation rates can have on the flammable cloud size. Figure 6 shows how increasing the ventilation rate from 5 to 10 air changes per hour (ACH) reduces the maximum flammable cloud size by more than 20% in case of thermal runaway of a single battery module.

Figure 6 Reduction of flammable cloud size in a battery room for varying ventilation rates (Warner et al, 2018)



Also the location of the ventilation ducts can have a significant impact on flammable cloud size, as shown in Figure 7, resulting in a 55 to 75% reduction in flammable cloud size upon selection of the right location of air extraction ducts.

Figure 7 Effect of location of ventilation (30 ACH) on flammable cloud size in container (Huser, 2019)



CFD dispersion simulations show that in a typical battery container (without external ventilation), failure of a single battery rack (consisting of about 15 to 20 battery modules) may result in a 50% volume filling of an equivalent stoichiometric gas cloud. This gas cloud contains gradients of gas concentrations and air. If the gas discharge rate is high enough (relative to external ventilation), the atmosphere inside the container will become saturated, reducing the size of the flammable cloud. If ventilation is increased, then the flammable cloud size increases with increasing ventilation rates. This is why ventilation is mainly useful when the thermal runaway can be limited to one of just a few battery modules.

5.2.2 Injection of Inert Gas (CO_2)

Simulations were performed using a one dimensional model for a free propagating premixed flame for increasing amounts of CO_2 as firefighting agent and for an equivalence ratio of 1.1. The results of the simulations are given in Figure 8 and Figure 9 (initial mixtures at 298 K). The simulations are based on the composition of gases as specified in specified in Figure 24, corresponding to the average composition of flammable gases produced during thermal runaway of Li-Ion pouch cells provided by SAFT.

Figure 8 and Figure 9 give respectively laminar burning velocities and adiabatic flame temperatures as calculated by Cantera using the 2 reaction mechanisms detailed above (GRI-Mech 3.0 and a model for combustion of H_2/CO/C_1-C_4 Compounds (Wang et al., 2007)). The laminar burning velocities and adiabatic flame temperature are given for an equivalence ratio of 1.1, for initial standard conditions (temperature and pressure) and for increasing concentrations of CO_2 as firefighting agent.

Figure 8 Laminar burning velocities for increasing concentrations of CO_2 as inert agent

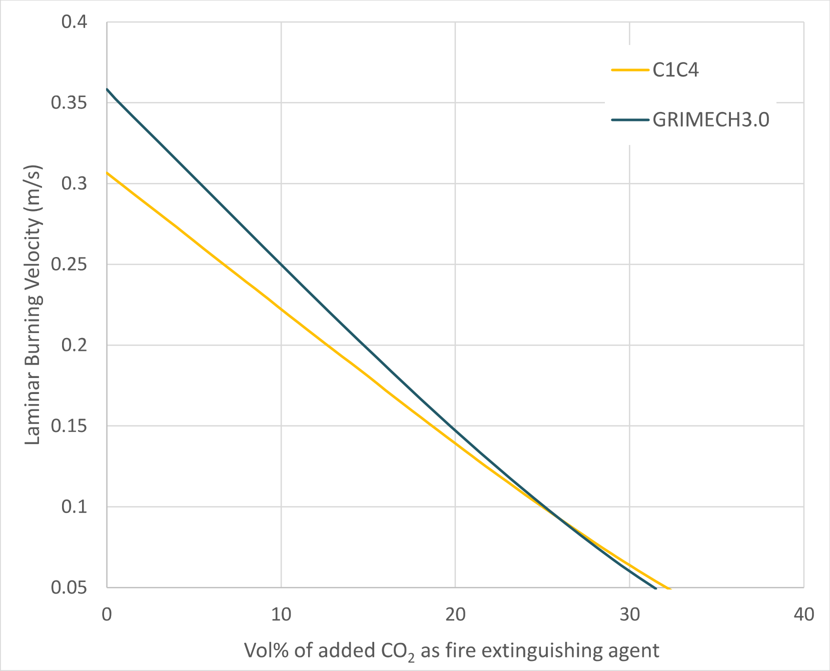
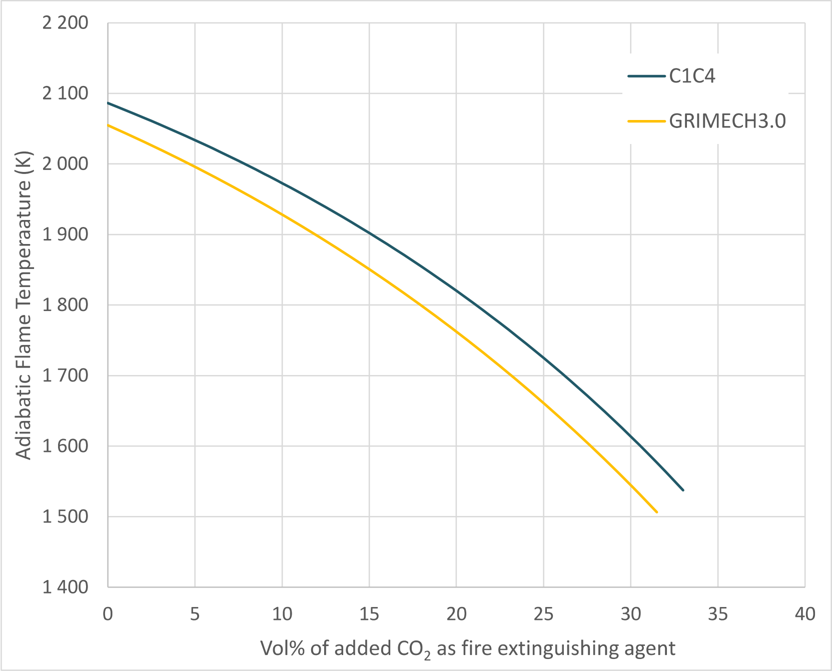
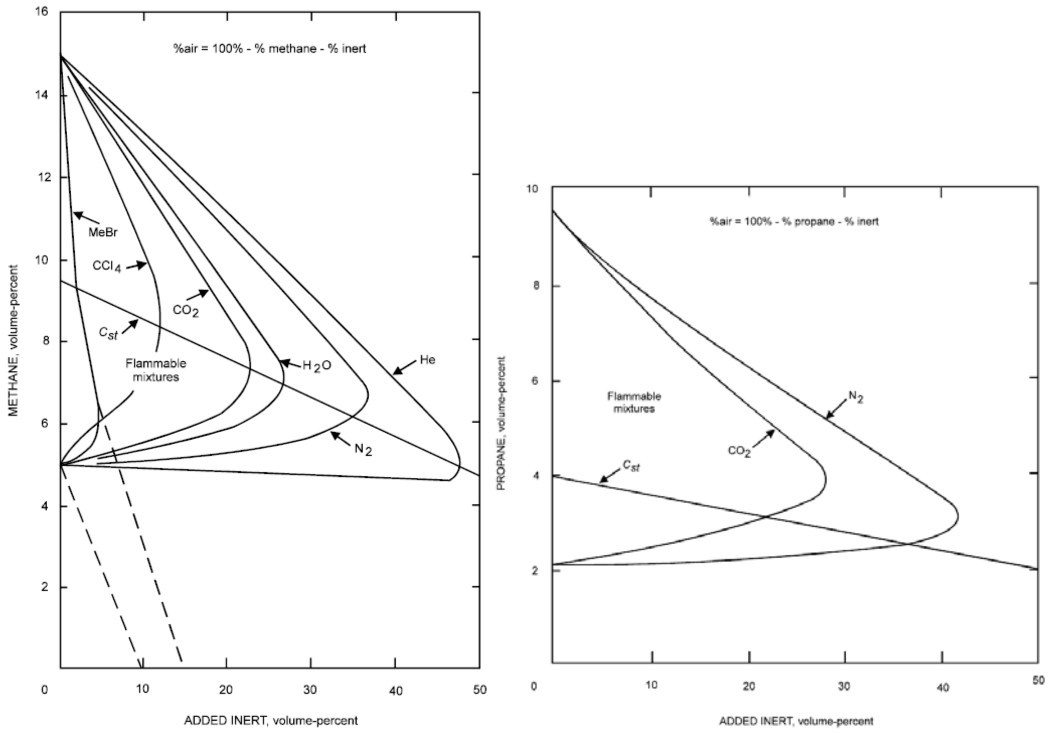


Figure 9 Adiabatic flame temperatures for increasing concentrations of CO_2 as inert agent



From the figures above, it can be seen that about 30 vol% of CO_2 needs to be added to inert the flammable mixture generated during thermal composition of SAFT Li-Ion pouch cells (assuming that flames with laminar combustion velocities lower than 0.05 m/s are unable to propagate). These results are in line with the concentrations of CO_2 required to inert methane/air and propane/air flames, as shown in Figure 10 (Zabetakis, 1999).

Figure 10 Flammability range of CH_4/air and C_3H_8/air mixtures as a function of concentration of inerting agents



5.2.3 Explosion Venting

If the presence of an explosive atmosphere inside a container upon thermal runaway of batteries cannot be avoided, blast relief panels may be necessary to mitigate the effects of an internal explosion upon ignition of the flammable gas mixture. The design of the relief panels (weight, size) is critical to assure that the panels react fast enough.

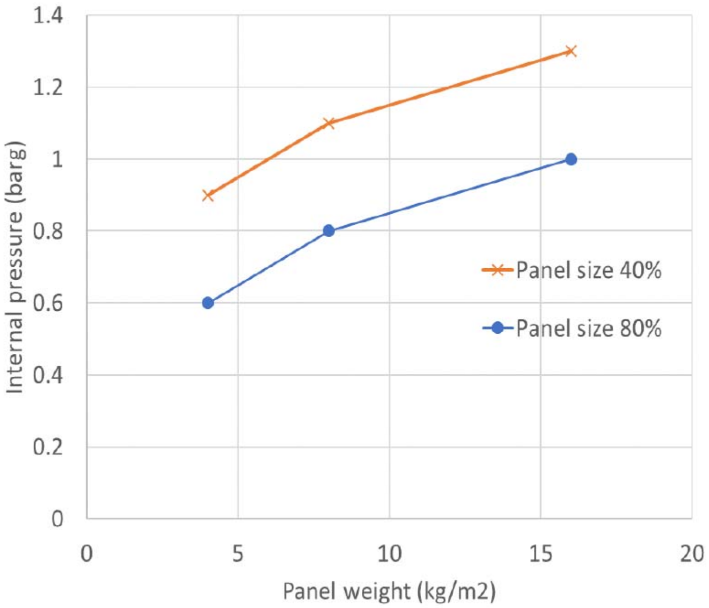
5.2.3.1 CFD Calculations by DNVGL (Warner et al., 2018)

A study was performed by Warner et al. (2018) on explosion and fire risk in ventilated battery rooms. They used experimentally-backed Computational Fluid Dynamics (CFD) simulations of off-gassing and explosion events. In the simulations, the composition of the gases discharged during thermal runaway of Li-Ion batteries were obtained experimentally. Based on these experiments, they conclude that the primary gases of interest, in order of descending approximate quantity are CO, H_2, CH_4, ethylene, HCl, ethane, methanol, ethanol, benzene, toluene, HF, HCN. Many of the gases end up in small enough quantities to be discarded, with CO, H_2, CH_4 and ethylene presenting the bulk of the explosion risk. This observation is very much in line with the experimental results obtained by Arora et al. (2018) in Table 15.

In the following example, the blast panel weight and size are varied to find the combination of parameters that yield sufficient reduction in explosion pressure. The dimensioning event is assumed to be an entire battery rack malfunction (thermal runaway) producing a 50% volume fill of a stoichiometric equivalent mixture. No external air ventilation is present in this case.

CFD simulations indicate that the explosion overpressure in the container exceeds 3 barg if it is a fully enclosed strong room. This pressure is too high to be contained and requires the use of pressure relief panels to lower the internal pressure acceptable levels. Assuming a design load of 1 barg overpressure on the container walls, one can determine the relief panel area and weight required to reduce the overpressure below the design threshold of the container. In this case, the relief panels would need to be lighter than 6 kg/m^2 and cover at least 40% of the roof of the container (see Figure 11). The explosion pressures shown Figure 11 are found by modeling the same explosion event several times with varying panel weight and size.

Figure 11 Influence of panel size and weight on maximum blast pressure in the container (Warner et al., 2018)

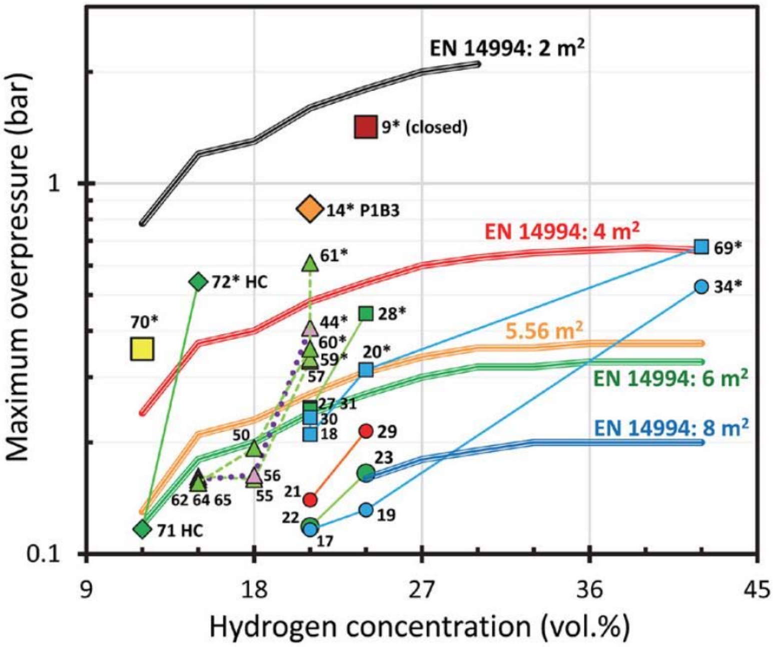


5.2.3.2 HySEA Project (FABIG, 2019)

As part of the HySEA project, Gexcon designed a test rig for 20-foot ISO containers and completed 66 vented hydrogen deflagration tests with homogeneous and inhomogeneous mixtures. A summary of this project is given in Appendix IV.

The reactivity of the gases vented during thermal runaway of Li-Ion batteries (see Appendix I) can be compared with the reactivity of lean hydrogen mixtures (12 to 15 vol% in air). For these mixtures, the maximum measured overpressures in the HySEA project vary from 100 mbarg to 600 mbarg for an explosion vent panel with a size of 40% of the roof surface and for a high degree of congestion in the container (see Figure 12).

Figure 12 Results of hydrogen explosion testing in a 20 foot ISO container (FABIG, 2019)



5.2.3.3 Simulation of Peak Pressure in Vented Explosion in the Battery Container

A basic mathematical model for estimating peak overpressure attained in vented explosions of hydrogen was presented in a study by Sinha et al. (2018). The model focused on idealized cases of hydrogen, and was not applicable to realistic accidental scenarios involving the presence of obstacles, initial turbulent mixture, etc.

The underlying framework of the model was reformulated by Sinha et al. to overcome these limitations. The flame shape computations are simplified. A more accurate and simpler formulation for venting is also introduced. Besides for hydrogen, the modified model accounts for thermo-physical properties of hydrocarbons and provides a table for fuel parameters to be used in the final equation for propane and methane. The model is also improved by addition of different sub-models to account for various realistic accidental scenarios.

Predictions from this simplified model are compared with experimentally measured values of overpressure for hydrogen and hydrocarbons and found to be in good agreement.

This model was applied for the geometry of a 20 foot ISO container, equipped with blast panels of different sizes. Since the reactivity of the gases vented during thermal runaway of Li-Ion batteries is similar to the reactivity of methane, the latter compound was used in the simulations. The calculations were performed under the assumption of both low and high congestion. The results are given in Figure 13 and Figure 14.

Figure 13 Peak pressure in battery container equipped with varying numbers of 18"x18" blast panels

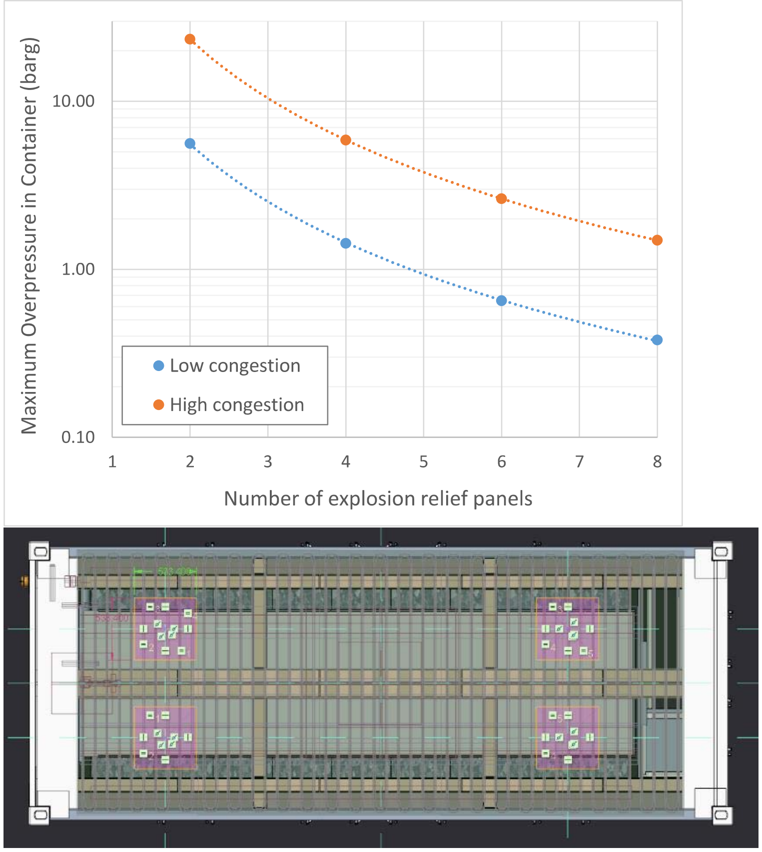
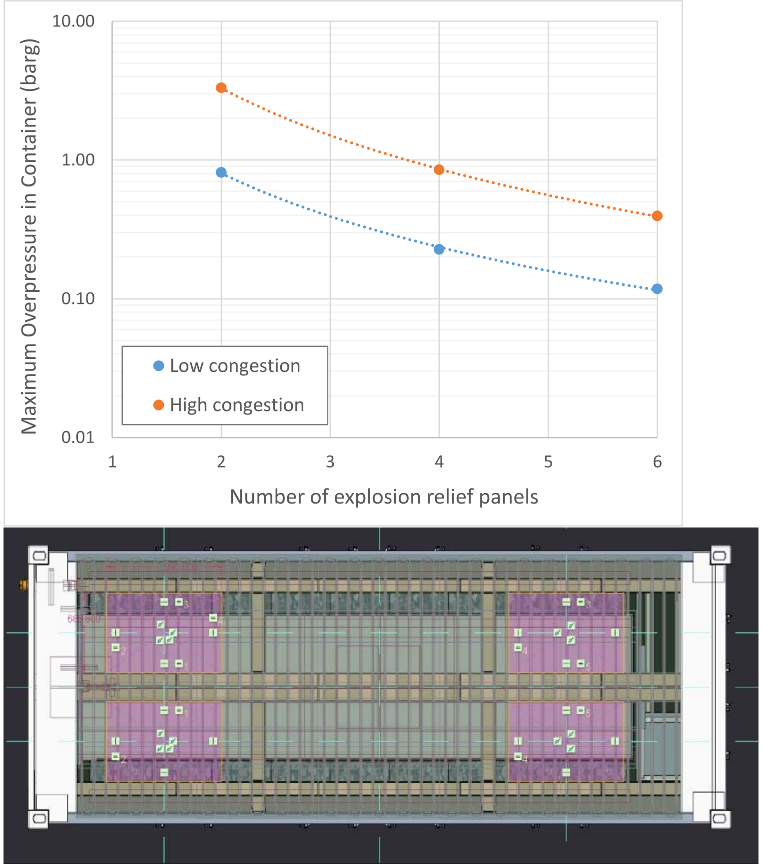


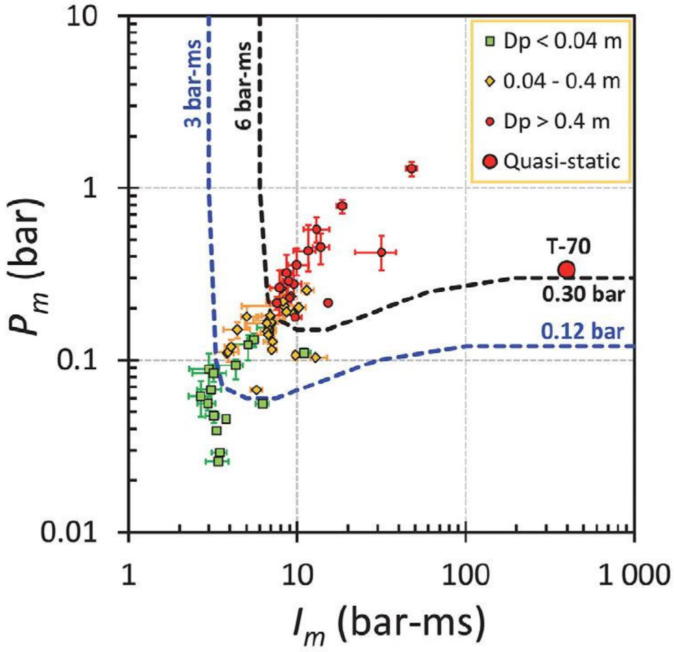
Figure 14 Peak pressure in battery container equipped with varying numbers of 24"x36" blast panels



A Pressure-Impulse diagram for a 20 foot ISO container can be found in Figure 15. In this diagram, regions corresponding to different damage levels in case of an internal explosion can be found.

- No/low damage of cointainer, corresponding with a plastic deformation of the container walls below 0.04 m.
- Repairable damage of container, corresponding with a plastic deformation of the container walls between 0.04 m and 0.4 m.
- Damage of container beyond repair, corresponding with a plastic deformation of the container walls beyond 0.4 m.

Figure 15 Pressure Impulse diagram for 20 foot ISO container



Based on the information presented in the figures above, it is recommended to install six 24”x36” blast panels in the roof of the battery container to limit the damage in case of an internal explosion due to runaway of Li-Ion batteries.

6 Fire Risks

Upon thermal runaway of Li-Ion batteries, flammable gases will be discharged (see Figure 24 for the average composition of these gases). Upon venting and ignition of these gases outside the container, a fire will occur. A description of some possible fire extinguishing systems is discussed in Appendix III.

Simulations with the software PHAST (vs. 6.7) were conducted to assess the impact of this fire. Several fire scenarios were modelled for several total durations of the thermal runaway of the Li-Ion batteries in a battery rack in the container (300 s, 600 s and 900 s total time).

Since the reactivity of the discharged flammable gases is comparable to that of methane (see previous chapters), the latter substance was selected to conduct the simulations. The description of the 3 modelled fire scenarios is given in Table 6. The discharge rate of produced flammable gases during the thermal runaway is assumed to be constant over the entire release duration.

Table 6 Fire Scenario Definition

Parameter	Value
Geometrical volume of container (m^3)	35
Free volume of Li-Ion battery container (m^3)	18
Size of flammable gas venting opening (m^2)	0.5
Flammable gas production per pouch (m^3)	0.0321
Total volume of flammable gas generated during thermal runaway of batteries in a single battery rack (Nm^3)	10.27
Flammable gas density (kg/Nm^3)	1.38
Lower Explosion Limit of generated gases (vol%)	13.3
Upper Explosion Limit of generated gases (vol%)	37.5
Scenario 1: thermal runaway of all batteries in a single battery rack lasting 300 s in total	
Total time of flammable gas release (s)	300
Temperature gases upon discharge in atmosphere via vent opening (K)[1]	373.15
Gas release rate (kg/s)	0.0474
Gas release rate (Nm^3/s)	0.0468
Velocity of flammable gases though vent opening (m/s)	0.0936
Scenario 2: thermal runaway of all batteries in a single battery rack lasting 600 s in total	
Total time of flammable gas release (s)	600
Temperature gases upon discharge in atmosphere via vent opening (K)[1]	373.15
Gas release rate (kg/s)	0.0237
Gas release rate (Nm^3/s)	0.0234
Velocity of flammable gases though vent opening (m/s)	0.0468
Scenario 3: thermal runaway of all batteries in a single battery rack lasting 900 s in total	
Total time of flammable gas release (s)	900
Temperature gases upon discharge in atmosphere via vent opening (K)[1]	373.15
Gas release rate (kg/s)	0.0158
Gas release rate (Nm^3/s)	0.0156
Velocity of flammable gases though vent opening (m/s)	0.0312

[1] The gas temperature of 100°C is an assumption. The hot gases released upon thermal runaway of batteries will mix with the ambient air inside the container before being vented into the atmosphere.

The geometry as shown in Figure 16 has been taken into account for the heat radiation modelling. It is assumed that the vent opening for discharging the flammable gases in the atmosphere is located in the center of the roof of the container and has a size of 0.5 m^2.

Figure 16 Considered container geometry for flammable gas venting and heat radiation calculations

The calculation results are given in Appendix V. This appendix also includes some heat radiation profiles for the different scenarios. A summary of the results is given in Table 7. Information on the impact of heat radiation on people and assets is given in Table 8 and Table 9.

From these tables, it is clear that heat radiation distances for significant effects are limited to only a few of meters from the container for all treated scenarios.

Table 7 Heat radiation distances (at 1 m above ground level and from the center of the vent opening)

Meteo condition	Distance to 3 kW/m^2	Distance to 5 kW/m^2	Distance to 8 kW/m^2
Scenario 1: thermal runaway of all batteries in a single battery rack lasting 300 s in total			
D5	6.5 m	5.6 m	4.8 m
F1.5	6.3 m	4 m	Not reached
Scenario 2: thermal runaway of all batteries in a single battery rack lasting 600 s in total			
D5	4.5 m	3.5 m	2.2 m
F1.5	4.6 m	2.0 m	Not reached
Scenario 3: thermal runaway of all batteries in a single battery rack lasting 900 s in total			
D5	3.2 m	2.3 m	Not reached
F1.5	3.8 m	Not reached	Not reached

D5: neutral stability of atmosphere, wind speed of 5 m/s (typical for daytime situation)
F1.5: stable atmosphere, wind speed of 1.5 m/s (typical for night time situation)

Table 8 Impact of heat radiation on people (HSE-BP-PS-003)

Heat Radiation Level (kW/m^2)	Impact on People
40	Immediate fatality.
20	Incapacitation, leading to fatality unless rescue is effected quickly.
12.5	Extreme pain within 20 seconds and movement to shelter is instinctive. Limiting flux for secondary fires.
5	Onset for lethal effects
4	Threshold value below which escape should always be possible.
3	Onset for irreversible effects

Table 9 Impact of heat radiation on structures (HSE-BP-PS-003)

Heat Radiation Level (kW/m^2)	Impact on Structures
5	windows break
< 8	no propagation of fire expected, without specific protective measures
8	blistering of paint
10	starting point for auto ignition of combustible materials (such as wood)
< 12	no propagation of fire expected, without sufficient cooling
15	piloted ignition of wood
16	limit of prolonged exposure for structures
20	concrete resists for several hours
35	auto ignition of wood
< 36	propagation of fire expected to hydrocarbon storage facilities, even with cooling
84	auto ignition of plastics
200	destruction of concrete within an hour

7 Toxic Dispersion Risks

7.1 Introduction

The average composition of gases produced during thermal runaway of Li-Ion pouch cells provided by SAFT is given in Figure 24. From this composition, it can be seen that the main toxic component present in significant quantities is carbon monoxide (representing about 30 vol% of the flammable gas mixture).

Upon venting of these gases outside the container without ignition, the toxic gas mixture will disperse in the atmosphere and dangerous toxic loads might be reached in the surroundings of the container.

Simulations with the software PHAST (vs. 6.7) were conducted to assess the impact of the dispersion of the toxic gases discharged during thermal runaway of the batteries in the atmosphere. Several dispersion scenarios were modelled for several total durations of the thermal runaway of the Li-Ion batteries in the container (300 s, 600 s and 900 s total time).The description of the 3 modelled dispersion scenarios is given in Table 10. The discharge rate of produced toxic gases is assumed to be constant over the entire duration. It is also assumed that the toxicity of the entire gas mixture is comparable to the toxicity of carbon monoxide (conservative assumption).

Table 10 Toxic Dispersion Scenario Definition

Parameter	Value
Geometrical volume of container (m^3)	35
Free volume of Li-Ion battery container (m^3)	18
Size of flammable gas venting opening (m^2)	0.5
Flammable gas production per pouch (m^3)	0.0321
Total volume of flammable gas generated during thermal runaway of all batteries in a single battery rack (Nm^3)	10.27
Flammable gas density (kg/Nm^3)	1.38
Scenario 1: thermal runaway of all batteries in a single battery rack lasting 300 s in total	
Total time of flammable gas release (s)	300
Temperature gases upon discharge in atmosphere via vent opening (K)[1]	373.15
Gas release rate (kg/s)	0.0474
Gas release rate (Nm^3/s)	0.0468
Velocity of flammable gases though vent opening (m/s)	0.0936
Scenario 2: thermal runaway of all batteries in a single battery rack lasting 600 s in total	
Total time of flammable gas release (s)	600
Temperature gases upon discharge in atmosphere via vent opening (K)[1]	373.15
Gas release rate (kg/s)	0.0237
Gas release rate (Nm^3/s)	0.0234
Velocity of flammable gases though vent opening (m/s)	0.0468
Scenario 3: thermal runaway of all batteries in a single battery rack lasting 900 s in total	
Total time of flammable gas release (s)	900
Temperature gases upon discharge in atmosphere via vent opening (K)[1]	373.15
Gas release rate (kg/s)	0.0158
Gas release rate (Nm^3/s)	0.0156
Velocity of flammable gases though vent opening (m/s)	0.0312

[1] The gas temperature of 100°C is an assumption. The hot gases released upon thermal runaway of batteries will mix with the ambient air inside the container before being vented into the atmosphere.

The geometry as shown in Figure 16 has been taken into account for the toxic gas dispersion modelling. It is assumed that the vent opening for discharging the flammable gases in the atmosphere is located in the center of the roof of the container and has a size of 0.5 m^2.

The calculation results are given in Appendix VI. A summary of the results is given in Table 11. Information on the impact of carbon monoxide on people is given in Section 6.2. From these tables, it is clear that toxic concentrations leading to significant effects on people upon short duration exposures (> 1000 ppm during minutes) are limited to only a few of meters from the container for all treated scenarios. Furthermore, these dangerous concentrations can only be found at elevation and do not exist at ground level because of the rise of the hot gases.

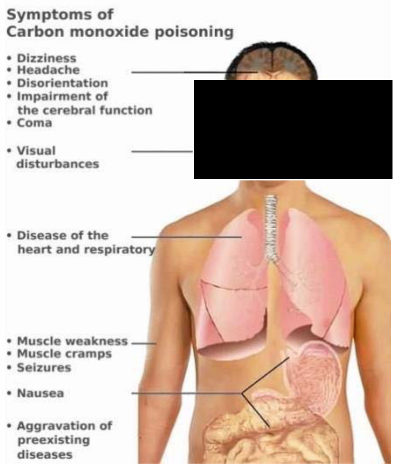
Table 11 Maximum toxic dispersion distances (in meters from the center of the vent opening)

Meteo condition	200 ppm	400 ppm	800 ppm	1600 ppm	3200 ppm
Scenario 1: thermal runaway of all batteries in a single battery rack lasting 300 s in total					
D5	22.6	15.4	10.4	6.9	4.4
F1.5	77.0	51.3	32.5	18.7	8.4
Scenario 2: thermal runaway of all batteries in a single battery rack lasting 600 s in total					
D5	16.0	11.0	7.5	5.0	3.3
F1.5	57.9	39.0	24.9	14.6	7.1
Scenario 3: thermal runaway of all batteries in in a single battery rack lasting 900 s in total					
D5	13.1	9.0	6.2	4.2	2.7
F1.5	49.0	33.0	21.2	12.6	6.3

D5: neutral stability of atmosphere, wind speed of 5 m/s (typical for daytime situation)
F1.5: stable atmosphere, wind speed of 1.5 m/s (typical for night time situation)

7.2 Toxicity of Carbon Monoxide

Carbon monoxide is not toxic to all forms of life. Its harmful effects are due to binding with hemoglobin so its danger to organisms that do not use this compound is doubtful. It thus has no effect on photosynthesizing plants. It is easily absorbed through the lungs. Inhaling the gas can lead to hypoxic injury, nervous system damage and even death. Different people and populations may have different carbon monoxide tolerance levels. On average, exposures at 100 ppm or greater is dangerous to human health. In the US, the OSHA limits long-term workplace exposure levels to less than 50 ppm averaged over an 8-hour period. In addition, employees are to be removed from any confined space if an upper limit ("ceiling") of 100 ppm is reached. Carbon monoxide exposure may lead to a significantly shorter life span due to heart damage. The carbon monoxide tolerance level for any person is altered by several factors, including activity level, rate of ventilation, a pre-existing cerebral or cardiovascular disease, cardiac output, anemia, sickle cell disease and other hematological disorders, barometric pressure and metabolic rate.


[redacted]

The main manifestations of carbon monoxide poisoning develop in the organ systems most dependent on oxygen use, the central nervous system and the heart. The initial symptoms of acute carbon monoxide poisoning include headache, nausea, malaise and fatigue. These symptoms are often mistaken for a virus such as influenza or other illnesses such as food poisoning or gastroenteritis. Headache is the most common symptom of acute carbon monoxide poisoning; it is often described as dull, frontal, and continuous. Increasing exposure produces cardiac abnormalities including fast heart rate, low blood pressure and cardiac arrhythmia. Central nervous system symptoms include delirium, hallucinations, dizziness, unsteady gait, confusion, seizures, central nervous system depression, unconsciousness, respiratory arrest and death.

One of the major concerns following acute carbon monoxide poisoning is the severe delayed neurological manifestations that may occur. Problems may include difficulty with higher intellectual functions, short term memory loss, dementia, amnesia, psychosis, irritability, a strange gait, speech disturbances, Parkinson's disease-like syndromes, cortical blindness, and a depressed mood. Depression may occur in those who did not have pre-existing depression. These delayed neurological sequelae may occur in up to 50% of poisoned people after 2 to 40 days. It is difficult to predict who will develop delayed sequelae; however, advanced age, loss of consciousness while poisoned, and initial neurological abnormalities may increase the chance of developing delayed symptoms.

Table 12 Toxicity of carbon monoxide

Concentration (ppm)	Effect
35	Headache and dizziness within six to eight hours of constant exposure
100	Slight headache in two to three hours
200	Slight headache within two to three hours; loss of judgment
400	Frontal headache within one to two hours
800	Dizziness, nausea, and convulsions within 45 min; insensible within 2 hours
1600	Headache, increased hart rate, dizziness, and nausea within 20 min; death in less than 2 hours
3200	Headache, dizziness and nausea in five to ten minutes. Death within 30 minutes.
6400	Headache and dizziness in one to two minutes. Convulsions, respiratory arrest, and death in less than 20 minutes.
12800	Unconsciousness after 2–3 breaths. Death in less than three minutes.

Sources:

- Goldstein M (December 2008).”Carbon monoxide poisoning”. Journal of Emergency Nursing. 34 (6): 538–42 doi:10.1016/j.jen.2007.11.014. PMID 19022078.
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Some threshold values for carbon monoxide are given in the table below:

Table 13 Threshold values for carbon monoxide

Threshold	Value (ppm)
ERPG-1	200
ERPG-2	350
ERPG-3	500
AEGL-2 10 minutes	420
AEGL-2 30 minutes	150
AEGL-2 60 minutes	83
AEGL-2 4 hours	33
AEGL-2 8 hours	27
AEGL-3 10 minutes	1700
AEGL-3 30 minutes	600
AEGL-3 60 minutes	330
AEGL-3 4 hours	150
AEGL-3 8 hours	130

- ERPG-1 is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing other than mild, transient health effects.

- ERPG-2 is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing irreversible or other serious adverse effects.
- ERPG-3 is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without life-threatening health effects (AIHA 2008).
- AEGL-2 is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.
- AEGL-3 is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death.

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9 Appendix I: Characterization of Gases discharged during Runaway

9.1 Composition of Flammable Gas Generated during Thermal Runaway

Flammable gases are generated during thermal runaway of Li-Ion batteries. In the following sections, experimental data are listed about the composition of flammable gases discharged during thermal runaway of Li-Ion batteries.

9.1.1 Arora et al. (2018)

SAFT engaged the company Exponent to characterize the flammable gas released from Li-Ion pouch cells when heated to thermal runaway failure. The tests were conducted on 3 Li-Ion pouch cells of 17.5 Ah. The testing involved the following activities:

- Charging the cells (per SAFT specifications);
- Controlled heating of the 3 cells until thermal runaway failure, inside a sealed 60 l chamber;
- Collection of the vented gases and subsequent composition analysis via gas chromatography with flame ionization detection (GC-FID).

A picture of a Li-Ion pouch cell provided by SAFT is given in Figure 17. The specifications of the 3 tested Li-Ion pouch cells and the generated amount of flammable gas per pouch are given in Table 14. The composition of the flammable gases generated and discharged during thermal runaway of each of the 3 pouch cells is given in Table 15.

Figure 17 Picture of a Li-Ion pouch cell by SAFT

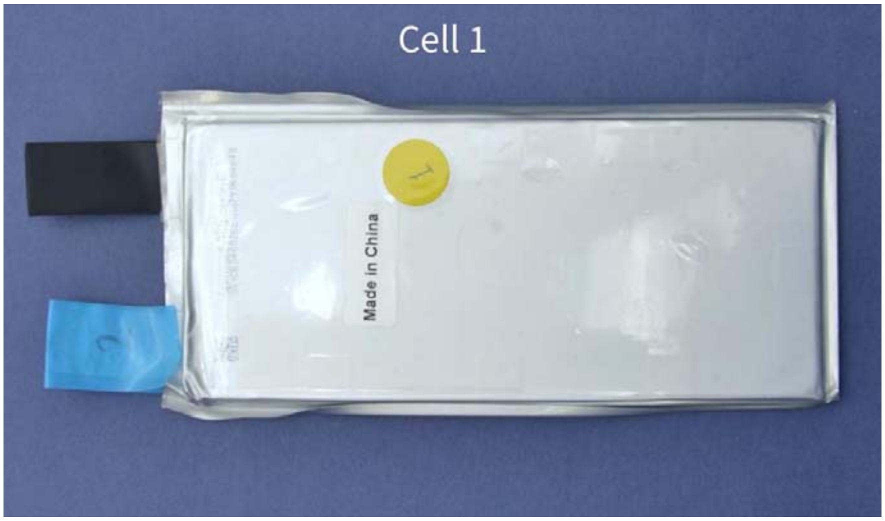


Table 14 Specifications of the 3 Li-Ion pouch cells provided by SAFT for testing

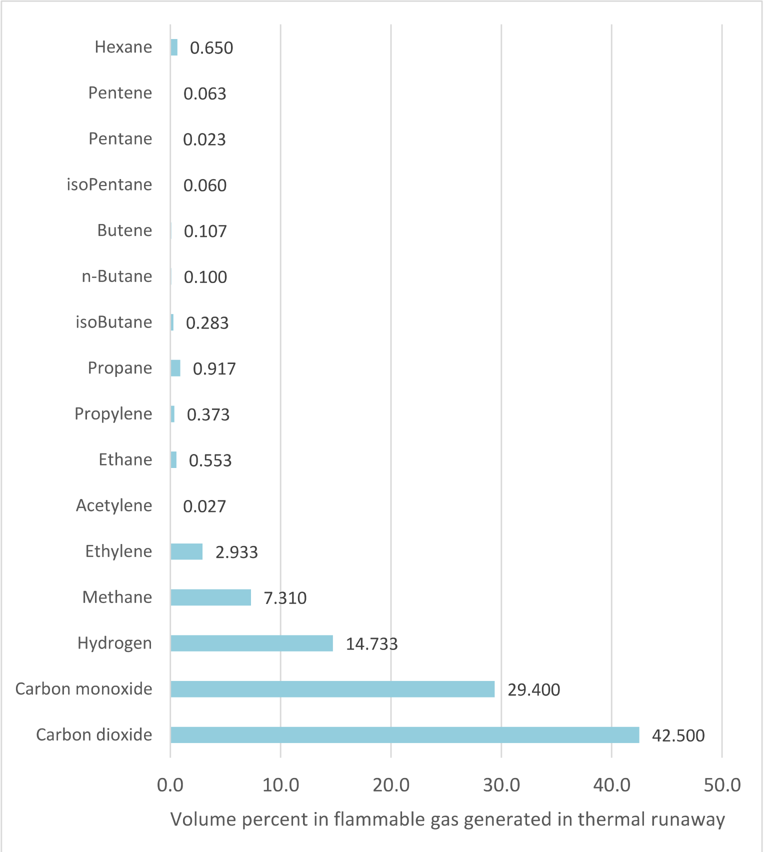
Property	Cell 1	Cell 2	Cell 3
Voltage (V)	4.2	4.2	4.2
AC Imp (mΩ)	2.0	2.1	2.1
Mass (g)	290.6	290.7	290.9
Mass after test (g)	163.7	190.9	181.8
Generated amount of gas (Nm^3)	0.0304	0.0340	0.0319
Density of gas (kg/Nm^3)	1.41	1.36	1.38

Table 15 Composition of flammable gas generated during thermal runaway of 3 Li-Ion pouch cells

Component	Cell 1 (vol%)	Cell 2 (vol%)	Cell 3 (vol%)
Carbon dioxide (CO_2)	44.30	41.00	42.20
Carbon monoxide (CO)	28.20	29.80	30.20
Hydrogen (H_2)	14.10	16.00	14.10
Methane (CH_4)	6.59	7.14	8.20
Ethylene (C_2H_4)	3.17	3.24	2.39
Acetylene (C_2H_2)	0.04	0.03	0.01
Ethane (C_2H_6)	0.54	0.59	0.53
Propylene (C_3H_6)	0.71	0.26	0.15
Propane (C_3H_8)	1.04	0.82	0.89
isoButane (iC_4H_{10})	0.33	0.25	0.27
n-Butane (C_4H_{10})	0.12	0.09	0.09
Butene (C_4H_8)	0.12	0.10	0.10
isoPentane (C_5H_{12})	0.09	0.05	0.04
Pentane (C_5H_{12})	0.03	0.02	0.02
Pentene (C_5H_{10})	0.08	0.01	0.10
Hexane (C_6H_{14})	0.63	0.72	0.60

The test results for the 3 pouch cells are quite similar. In the 3 cases, large amounts of carbon dioxide (42 to 44 vol%) and carbon monoxide (28 to 30 vol%) were measured in the discharged gases. Hydrogen is present in quantities varying from 14 to 16 vol%, while methane contributes 6 to 8 vol% and ethylene 2 to 3 vol%. The average values for flammable gas composition can be found in Figure 18.

Figure 18 Average composition of flammable gas generated during thermal runaway of Li-Ion pouch cells



9.1.2 Golubkov et al. (2014)

Golubkov et al (2014) analysed the gas composition of the vented gas emitted from 3 different 18650 batteries, i.e. an LCO (Lithium Cobalt Oxide: $LiCoO_2$), LNMCO (Lithium Nickel Manganese Cobalt Oxide: LiN-iMnCoO_2) and LFP (Lithium Iron Phosphate: $LiFePO_4$) lithium batteries. The specifications for these batteries are given in Table 16.

Table 16 Specifications of different types of Li-Ion batteries used in experiments by Golubkov et al. (2014)

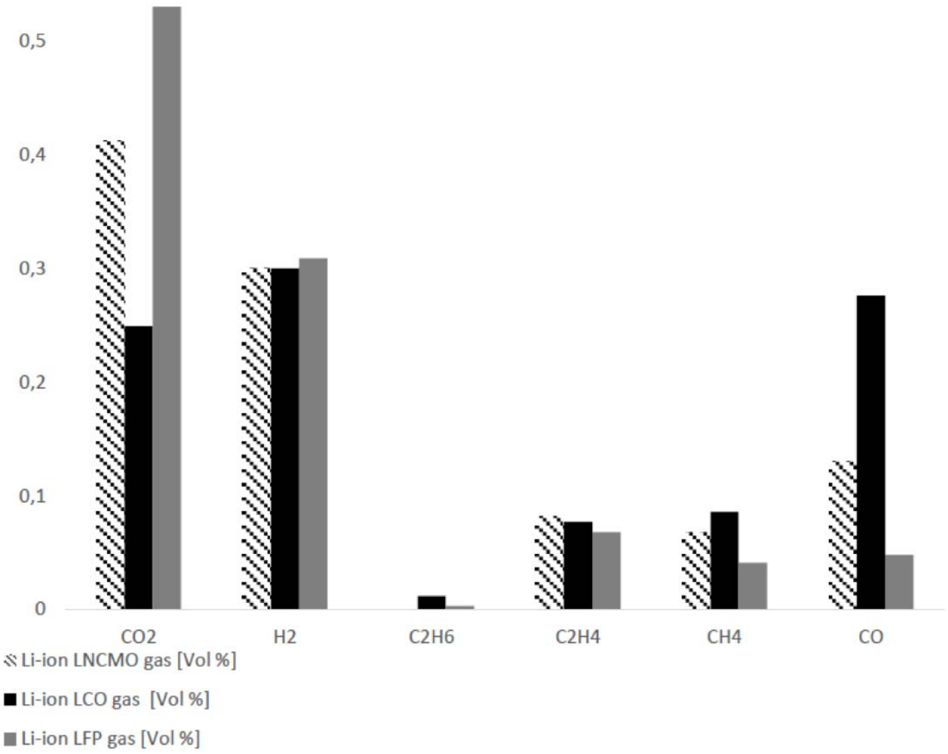
Property	LCO	LNMCO	LFP
Cell mass (g)	44.3	43.0	38.8
Cell capacity (Ah)	2.6	1.5	1.1
Cell minimum voltage (V)	3.0	3.0	2.5
Cell maximum voltage (V)	4.2	4.1	3.5
Electrolyte solvents	DMC:EMC:EC (6:2:1)	DMC:EMC:EC:PC (7:1:1:1)	DMC:EMC:EC:PC (4:2:3:1)
Cathode material	$LiCoO_2$ $Li(Ni_{0.5}Mn_{0.25}Co_{0.25})O_2$	$Li(Ni_{0.5}Mn_{0.25}Co_{0.10})O_2$	$LiFePO_4$
Anode material	Graphite	Graphite	Graphite

The batteries contain flammable materials in the form of Li, electrolytes and graphite. When an 18650 battery is overheated or experiences a thermal runaway, the pressure inside the battery will increase. If the battery reaches a temperature of about 150°C, then a rupture disc will open and relief the pressure and flammable gases, mists and particles will be vented into the surroundings. A picture of an 18650 battery is given in Figure 19.

Figure 19 Picture of an 18650 Li-Ion battery after thermal runaway

The results of the gas composition measurements by Golubkov et al. are given in Figure 20. For all the 3 batteries the H_2 content was about 30 vol%. The generated gas also contains significant amounts of flammable hydrocarbons in the form of ethylene (C_2H_2) and methane (CH_4). The sum of CO_2 and CO was more or less constant, but the CO_2 and CO concentration varies for the 3 batteries. The LCO battery gave nearly 30 vol% CO while the LFP battery gave less than 5 vol% CO.

Figure 20 Composition of flammable gas generated during thermal runaway of 18650 Li-Ion batteries



9.1.3 Somandepalli et al. (2014)

To investigate the composition and flammability characteristics of gases discharged during thermal runaway of a Li-Ion pouch cells, Somandepalli et al. (2014) developed a test method in which thermal failure of a cell was initiated in an enclosed chamber filled with an inert gas (argon). After the cell vented, the resulting gases were collected in a sample canister and analysed for composition using gas chromatography-mass spectroscopy (GC-MS). Although the tested cells were vented into an inert environment, partial combustion could still take place due to the decomposition of the positive electrode active material, which releases oxygen during decomposition. For other cell chemistries that do not produce oxygen during thermal runaway, partial combustion is not expected in the inert chamber environment.

The amount of gas vented during a thermal runaway event and their composition is given in Table 17 for pouch cells at 3 different states of charge. The capacity of each of the pouch cells is 7.7 Wh and they have a volume of 0.014 liters. The volumes reported in Table 17 are referenced to standard pressure and temperature (25°C, 101325 Pa).

The table shows that the higher the state of the charge, the larger the amount of gases released. A pouch cell that is charged at 100% will generate more than twice the amount of gas than a cell that is charged at 50%.

Table 17 Amount and composition of flammable gas vented during thermal runaway of Li-Ion pouch cells

	State of Charge = 50%	State of Charge = 100%	State of Charge = 150%
Vented gas volume per cell (m^3)	$8 \cdot 10^{-4}$	$25 \cdot 10^{-4}$	$60 \cdot 10^{-4}$
Volume of vented gas per Wh (m^3)	$1 \cdot 10^{-4}$	$3.3 \cdot 10^{-4}$	$7.8 \cdot 10^{-4}$
Gas composition (in vol%)			
Carbon dioxide	32.3	30.0	20.9
Carbon monoxide	3.61	22.9	24.5
Hydrogen	31.0	27.7	29.7
Methane	5.78	6.39	8.21
Ethylene	5.57	2.19	10.8
Ethane	2.75	1.16	1.32
Propylene	8.16	4.52	0.013
Propane	0.68	0.26	2.54
Isobutane	0.41	0.20	0.13
n-Butane	0.67	0.56	0.39
Butenes	2.55	1.58	0.60
Isopentane	0.45	0.07	0.036
n-Pentane	1.94	0.73	0.30
Hexanes+	4.94	2.32	8.21
Benzene	0.14	0.11	0.33
Toluene	0.061	0.018	0.052
Ethylbenzene	0.009	0.002	0.003

9.2 Simulation of Reactivity and Flammability of Gases Generated During Thermal Runaway

9.2.1 Models

As part of this study, a simulation was performed of the reactivity and flammability of gases produced during thermal runaway of Li-Ion pouch cells provided by SAFT. Two different kinetic models were used in the simulations:

- The GRI-Mech 3.0 model (http://www.me.berkeley.edu/gri_mech/);
- A model for combustion of H_2/CO/C_1-C_4 Compounds (Wang, 2007);

9.2.1.1 GRI-Mech 3.0

GRI-Mech 3.0 is an optimized mechanism designed to model natural gas combustion, including NO formation and reburn chemistry. It is the successor to version 2.11. Improvements were made in the categories of updating the kinetics with recent literature results, including some new and improved target experiments to the optimization, expanding the mechanism and target selection, and examining the sensitivity to thermodynamics.

The CH kinetics important to prompt NO formation were altered in light of new measurements. New expressions were also used for the H + O_2 reactions, CH_3 + O_2, CH_2O + H and CH_2O decomposition. The methanol decomposition/chemical activation system was recomputed. The oxidation steps CH_3 + O and CH_2 + O_2 feature new branching paths.

The new mechanism contains 325 reactions (3 are duplicates because the sum of two rate parameter expressions is required) and 53 species (including argon). The final optimization to 77 targets altered 31 rate parameters.

For simulations including the effect of sodium compounds and/or potassium compounds as flame inhibitors, the GRI-Mech 3.0 mechanism was extended with a mechanism describing the combustion reaction chemistry of sodium compounds and potassium compounds (see also Section 3.2.1.3 and 3.2.1.4). The latter mechanism is referred to as the Extended Gri-Mech3.0 mechanism in the remainder of this chapter.

The extended mechanism was created by addition of the elementary reactions involving sodium and potassium compounds to the elementary reactions of the GRI-Mech 3.0 mechanism. This can be done because no interactions are expected between potassium or sodium compounds and the parent fuel or its decomposition products. The action of potassium and sodium as inhibitor is not to interfere with the nature of the different elementary reactions involved in combustion, but to add reactions that compete with these elementary reactions and as such influence the relative sensitivity of these different reactions. The addition of sodium or potassium will increase the importance of radical termination reactions.

9.2.1.2 Model for Combustion of H_2/CO/C_1-C_4 Compounds (Wang et al., 2007)

The kinetic model for combustion of H_2/CO/C_1-C_4 compounds by Wang et al. (2007) was used in the calculations. This model includes 111 species and 784 reactions, applicable to a wide variety of combustion scenarios. The model incorporates recent thermodynamic, kinetic, and species transport updates relevant to high-temperature oxidation of hydrogen, carbon monoxide, and C_1-C_4 hydrocarbons. The model was developed on the basis of:

- An optimized reaction model for H_2/CO combustion;
- GRI-Mech1.2 and 3.0;
- A comprehensive reaction model for ethylene and acetylene combustion;
- Reaction mechanism for C_3 fuel combustion;
- 1,3-Butadiene oxidation at high temperatures.

9.2.2 Cantera

Simulations were performed with the software Cantera (Goodwin, 2017). Cantera is a suite of object-oriented software tools to solve problems involving chemical kinetics, thermodynamics, and/or transport processes. Cantera provides types (or classes) of objects representing phases of matter, interfaces between these phases, reaction managers, time-dependent reactor networks, and steady one-dimensional reacting flows. Cantera is currently used for applications including combustion, detonations, electrochemical energy conversion and storage, fuel cells, batteries, aqueous electrolyte solutions, plasmas, and thin film deposition. Cantera includes a set of models for representing steady-state, quasi-one-dimensional reacting flows, which can be used to simulate a number of common flames, such as:

- Freely-propagating premixed laminar flames;
- Burner-stabilized premixed flames;
- Counterflow diffusion flames;
- Counterflow (strained) premixed flames.

All of these configurations are simulated using a common set of governing equations within a 1D "flow" domain, with the differences between the models being represented by differences in the boundary conditions applied. The models are all based on finding solutions for the following set of equations:

Continuity equation (conservation of mass)	$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$
Momentum equation (conservation of momentum)	$\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u u) = -\nabla p + \rho g - \nabla \cdot \tau$
Energy equation (conservation of energy)	$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho u h) = -\nabla \cdot \mathrm{q} - \tau : (\nabla \mathrm{u}) + \frac{Dp}{Dt}$
Conservation of chemical **species** equation	$\frac{\partial \rho_i}{\partial t} + \nabla \cdot (\rho_i u_i) = \omega_i$

with:

ρ	mass density (kg/m^3)	τ	viscous stress tensor (kg/m/s^2)
t	time (s)	g	gravity constant (m/s^2)
u	three dimensional flow velocity (m/s)	$\nabla \cdot$	divergence operator
p	pressure (Pa)	∇	gradient operator
h	enthalpy (m^2/s^2)	:	contraction of pressure tensor & gradient
q	heat flux vector (J/m^2/s)		
ω_i	chemical source term of species I (kg/m^3/s)		
ρ_i	mass density of species i (kg/m^3)		
u_i	three dimensional velocity of species i (m/s)¤		

9.3 Model Predictions for Hydrogen, Methane and Propane

To check the setup of the model and the calculation routines, the laminar burning velocity for some non-inhibited flames (methane/air, propane/air and hydrogen/air flames at varying equivalence ratios) were calculated using the reaction mechanism of GRI-Mech3.0 and Wang et al. (2007). These reaction mechanisms are referred to as "GRI-Mech3.0" and "C1C4" in the following figures. The model predictions were compared to laminar burning velocity data published in literature. A good agreement was found between model predictions and literature data. For slightly rich mixtures (equivalence ratio of 1.1 to 1.2), the C1C4 model gives a bit lower predictions for methane/air flames and propane/air flames compared to most literature data.

Figure 21 Laminar burning velocities for uninhibited H_2/air flames at 298 K and 1 bar (Dahoe, 2005)

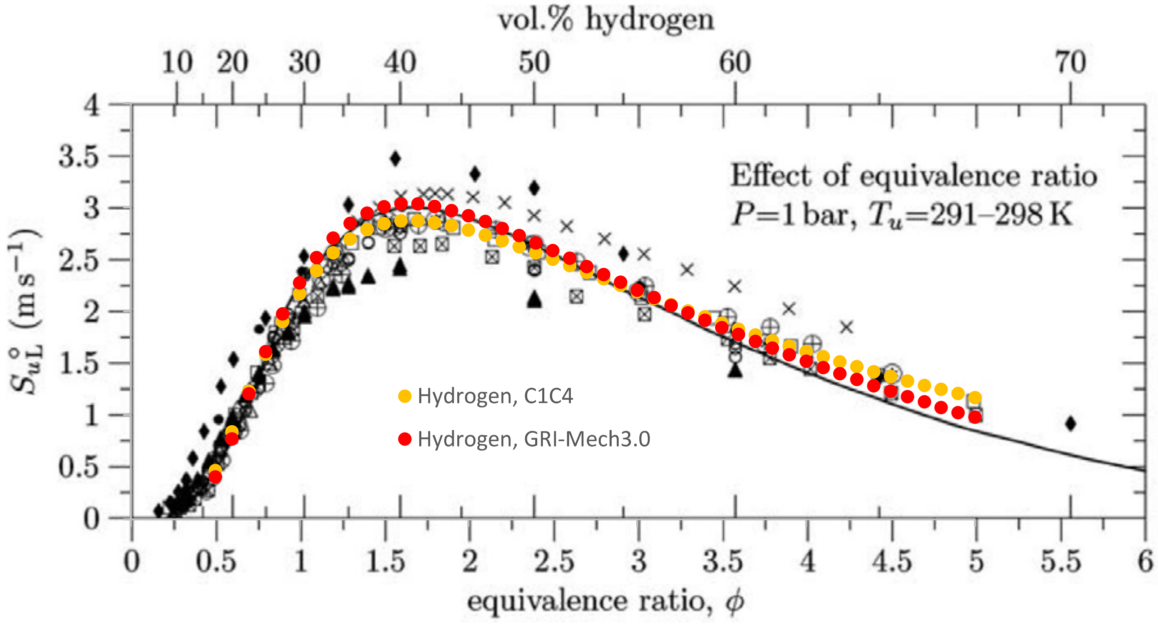


Figure 22 Laminar burning velocities for uninhibited CH_4/air flames at 298 K and 1 bar (Pizutti et al., 2017)

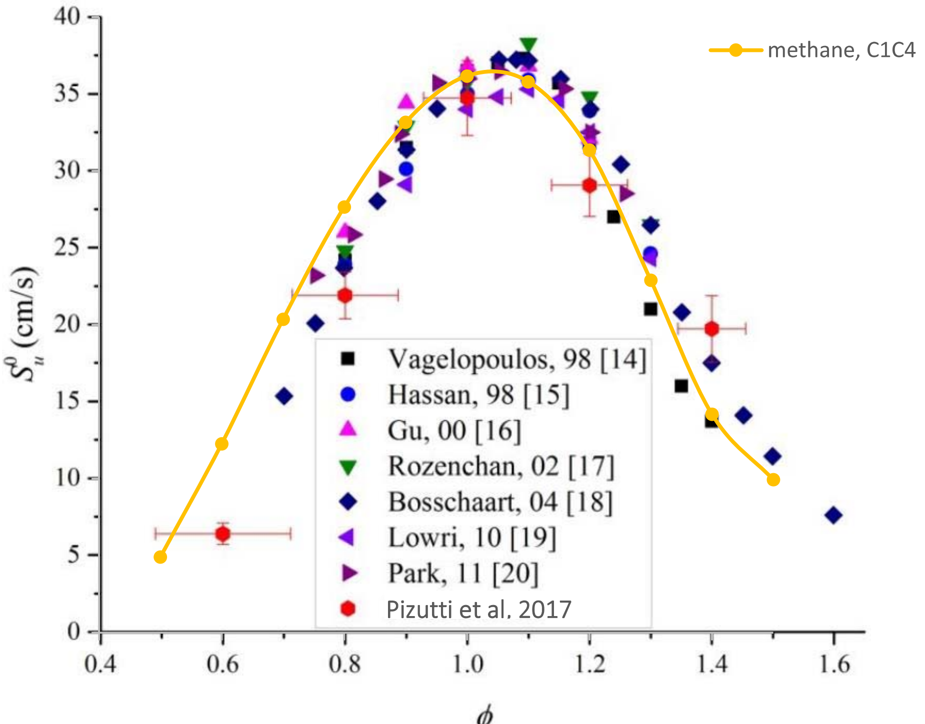
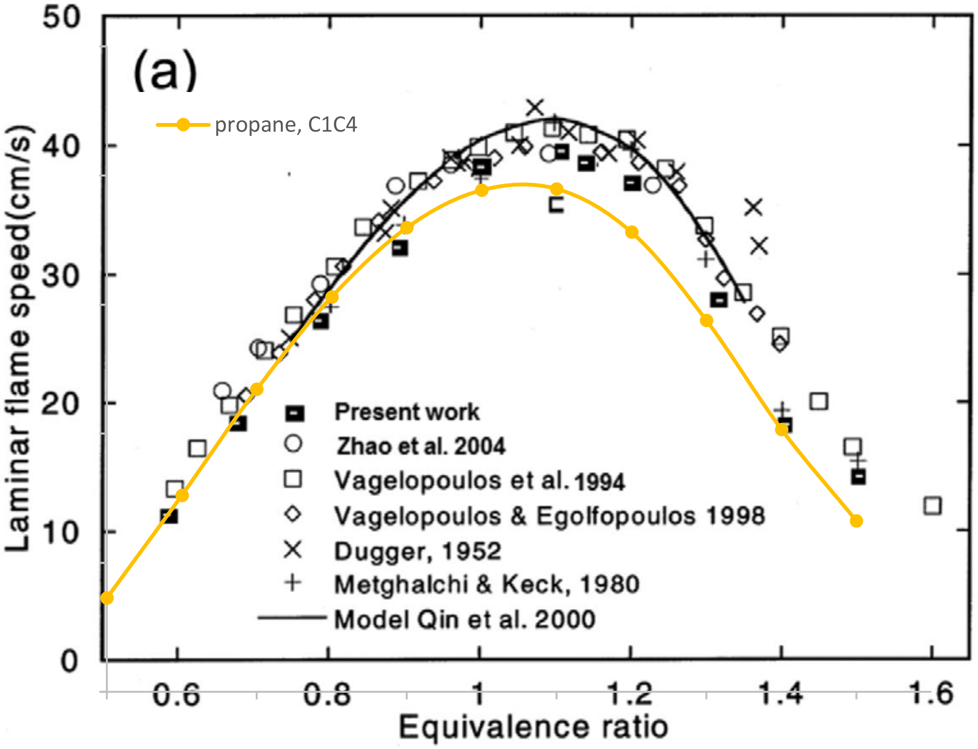


Figure 23 Laminar burning velocities for uninhibited C_3H_8/air flames at 300 K and 1 bar (Munzer and Kutiaba, 2016)



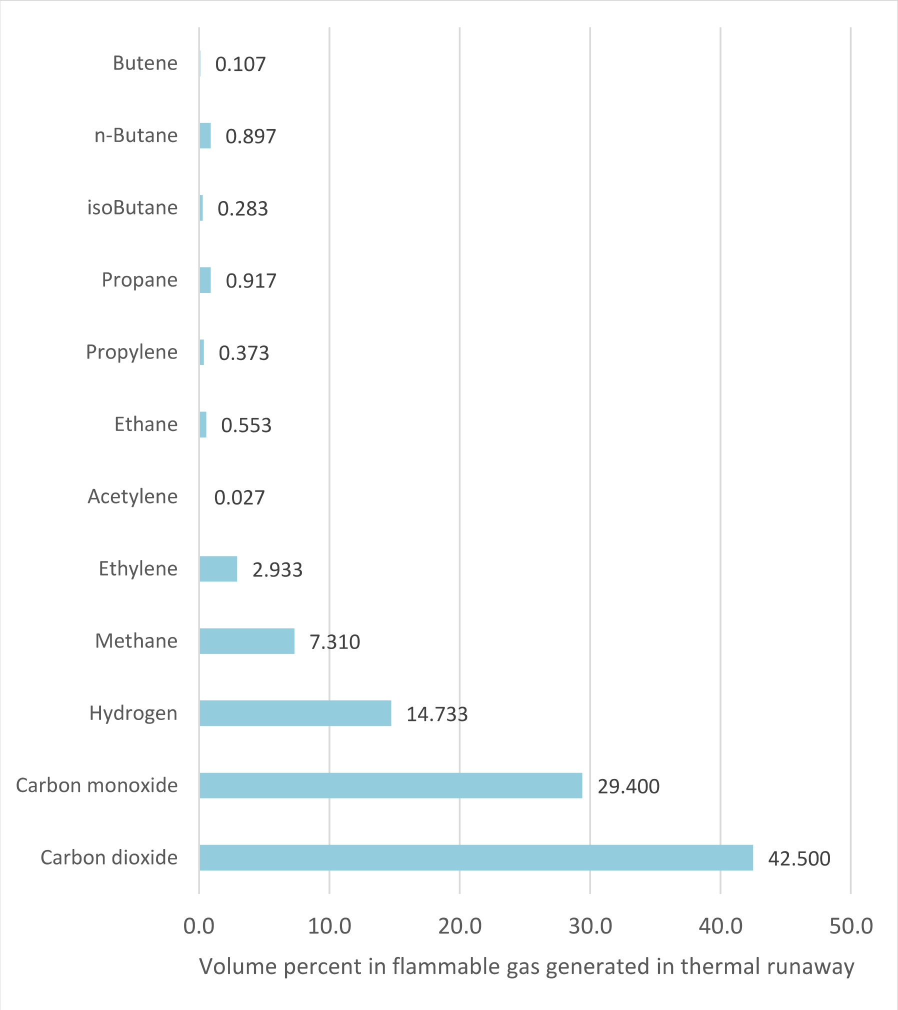
9.4 Model Predictions for Gases Produced during Thermal Runaway of SAFT Pouch Cells

Simulations were performed using a one dimensional model for a free propagating premixed flame for varying equivalence ratios. The results of the simulations are given the following figures (initial mixtures at 298 K). The simulations are based on the composition of gases as specified in specified in Figure 24, corresponding to the average composition of flammable gases produced during thermal runaway of Li-Ion pouch cells provided by SAFT.

Upon use of the C1C4 model, this composition is the same as the composition of Figure 18, except for the fact that the volume fractions of components heavier than C_4 are added to the volume fraction of n-Butane. This is done because the kinetic model used in the simulations does not include the combustion of components heavier than C_4. Because of the low contribution of these heavier fractions to the overall gas composition (< 1%), the impact of this modification is assumed to be negligible.

When using the GRI-Mech 3.0 model, propylene, C_4 compounds and heavier compounds were not taken into account since this model does not include these substances.

Figure 24 Composition of flammable gas used in simulations with Cantera



9.4.1 Laminar Burning Velocities

The following figures give laminar burning velocities as calculated by Cantera using the 2 reaction mechanisms detailed above (GRI-Mech 3.0 and a model for combustion of H_2/CO/C_1-C_4 Compounds (Wang et al., 2007)). The laminar burning velocities are given for different equivalence ratios in Figure 25 and for different volume percentages in air in Figure 26.

Figure 25 Laminar burning velocities for varying equivalence ratios (for initial standard conditions of the mixture)

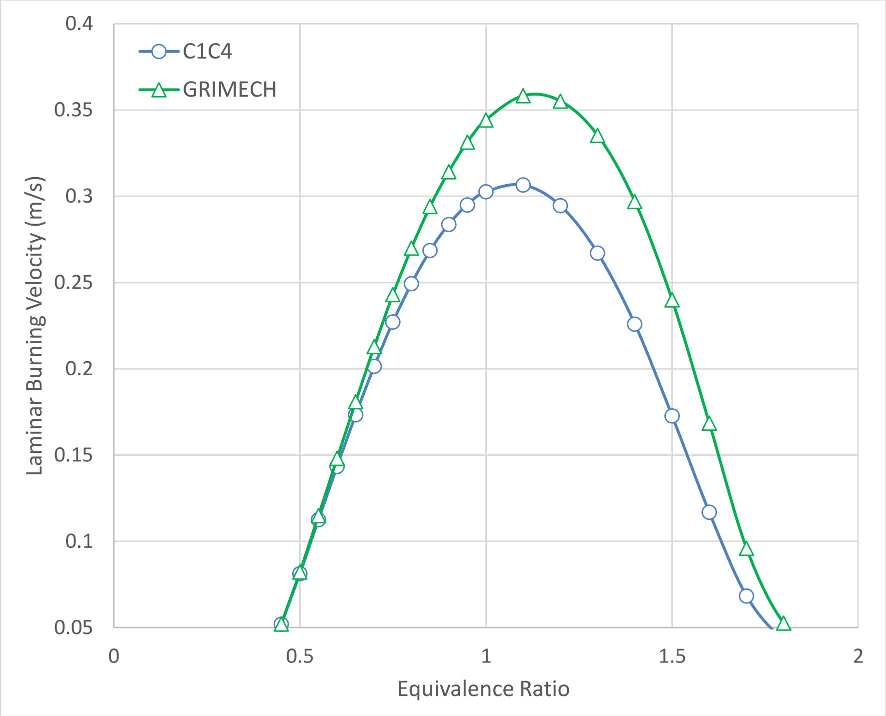
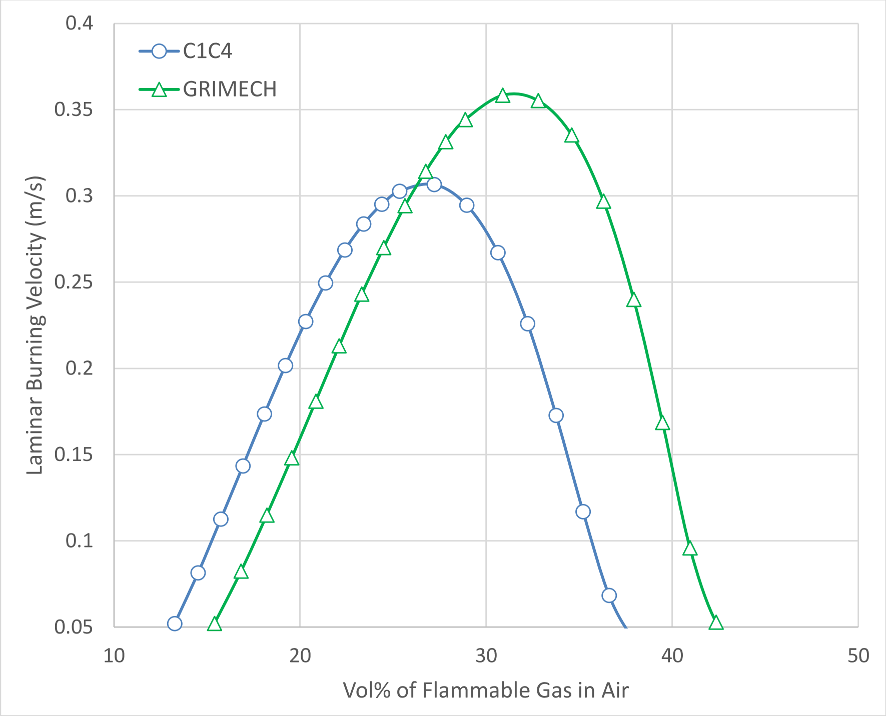


Figure 26 Laminar burning velocities for varying volume fractions (for initial standard conditions of the mixture)



9.4.2 Adiabatic Flame Temperatures

The following figures give adiabatic flame temperatures as calculated by Cantera using the 2 reaction mechanisms detailed above (GRI-Mech 3.0 and a model for combustion of $H_2/CO/C_1-C_4$ Compounds (Wang et al., 2007)). The adiabatic flame temperatures are given for different equivalence ratios in Figure 27 and for different volume percentages in air in Figure 28).

Figure 27 Adiabatic flame temperatures for varying equivalence ratios (for initial standard conditions of the mixture)

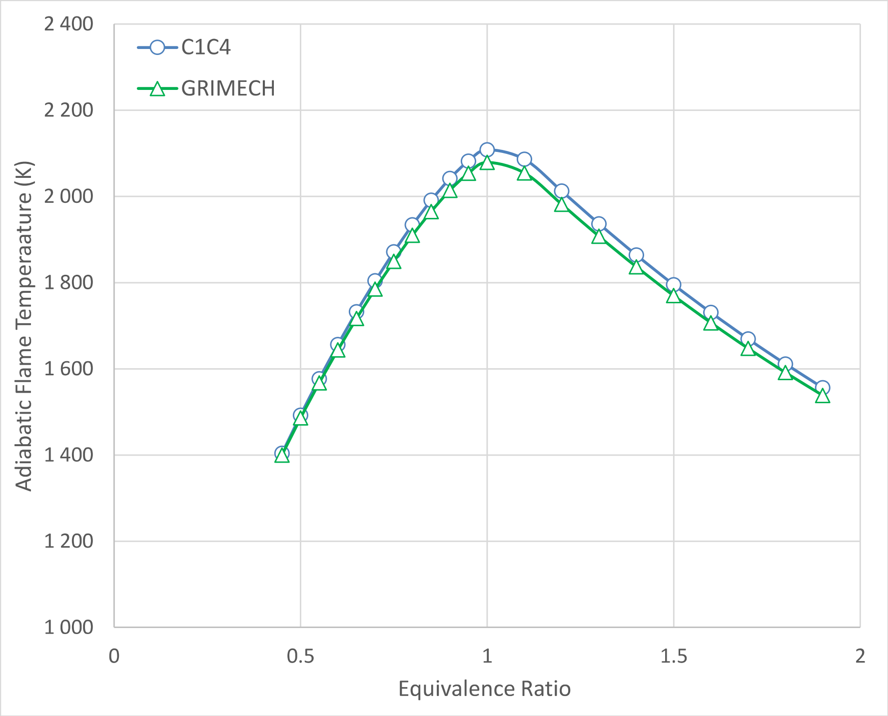
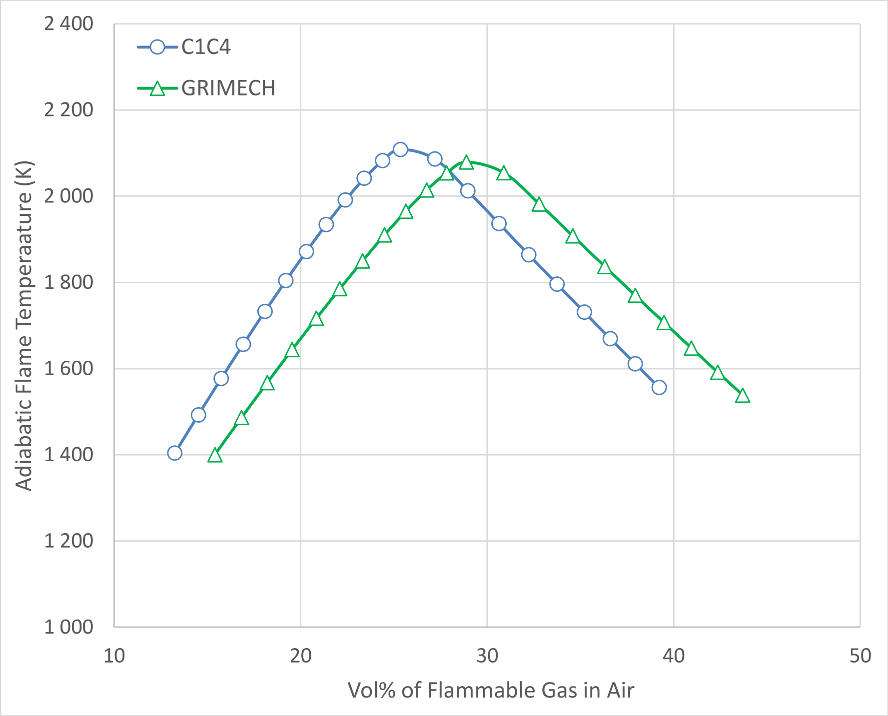


Figure 28 Adiabatic flame temperatures for varying volume fractions (for initial standard conditions of the mixture)



10 Appendix II: Gas Discharge Profiles and Concentrations in Container

The following figures show different possibilities for discharge profiles (Figure 29) and accumulated amounts (Figure 30) of the flammable gas in the battery container during thermal runaway of the Li-Ion batteries. The time-varying concentrations of flammable gas in the container were calculated using these different possibilities for discharge profiles and for varying external ventilation rates in the container (see Figure 31 and following). Based on these profiles, an external ventilation rate of 400 Nm3/h would be sufficient to keep the atmosphere inside the container below the Lower Flammability Limit of the gas discharged during thermal ruwaway of the Li-Ion batteries.

Figure 29 Possible flammable gas discharge profiles during thermal runaway of batteries inside container

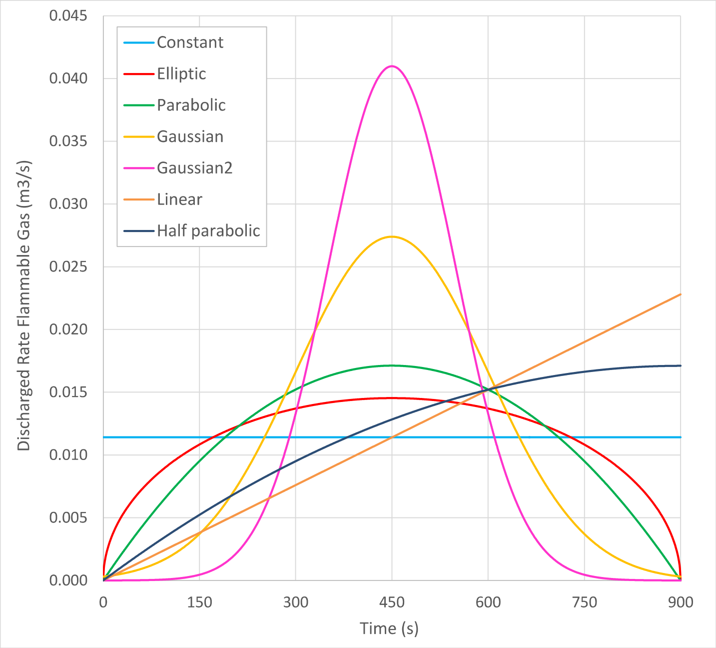


Figure 30 Total amount of flammable gas discharged for each of the discharge rate profiles

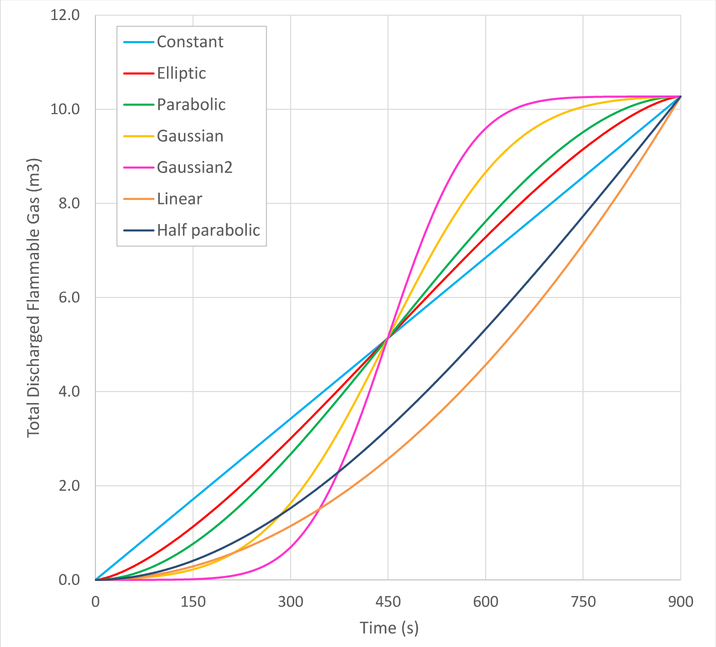


Figure 31 Flammable gas concentration in container for various ventilation rates (constant gas discharge profile)

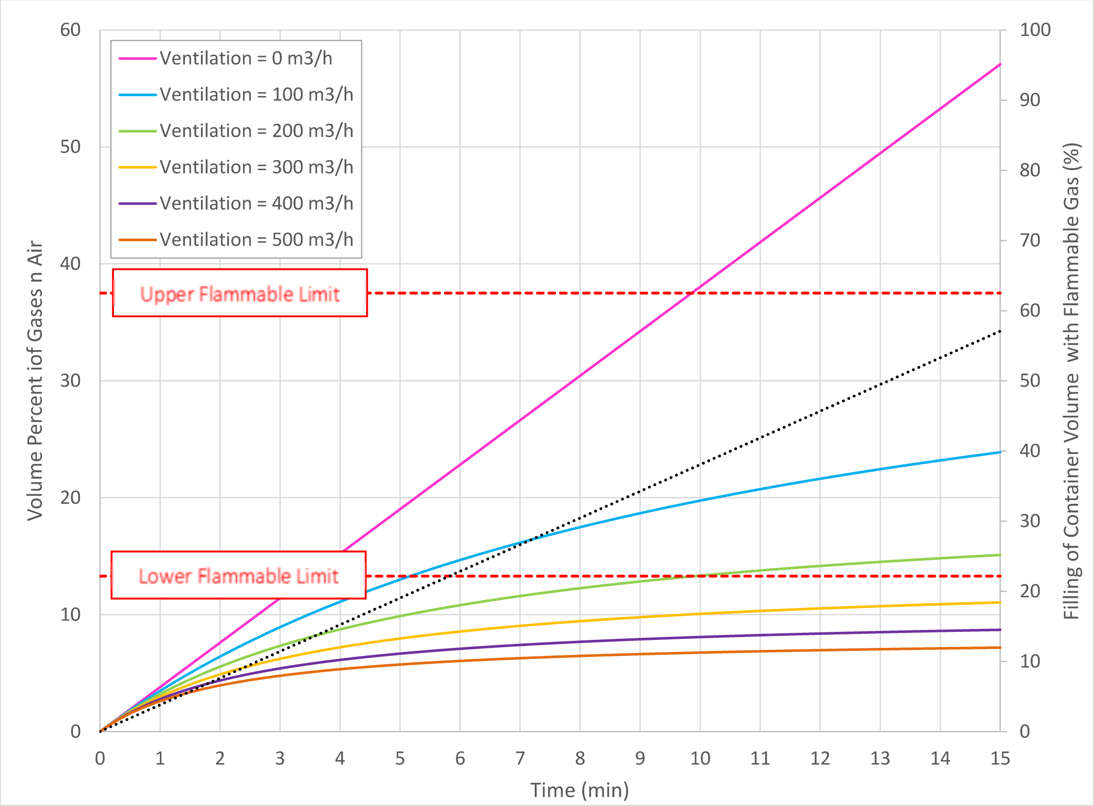


Figure 32 Flammable gas concentration in container for various ventilation rates (linear gas discharge profile)

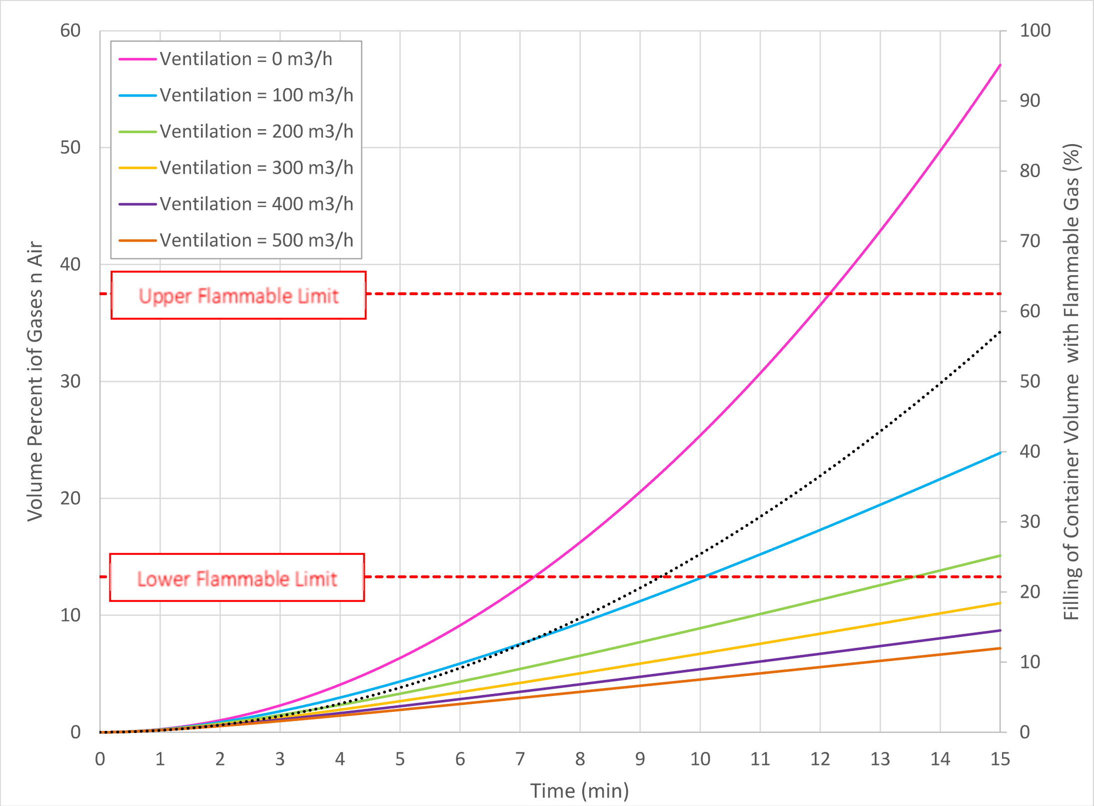


Figure 33 Flammable gas concentration in container for various ventilation rates (elliptic gas discharge profile)

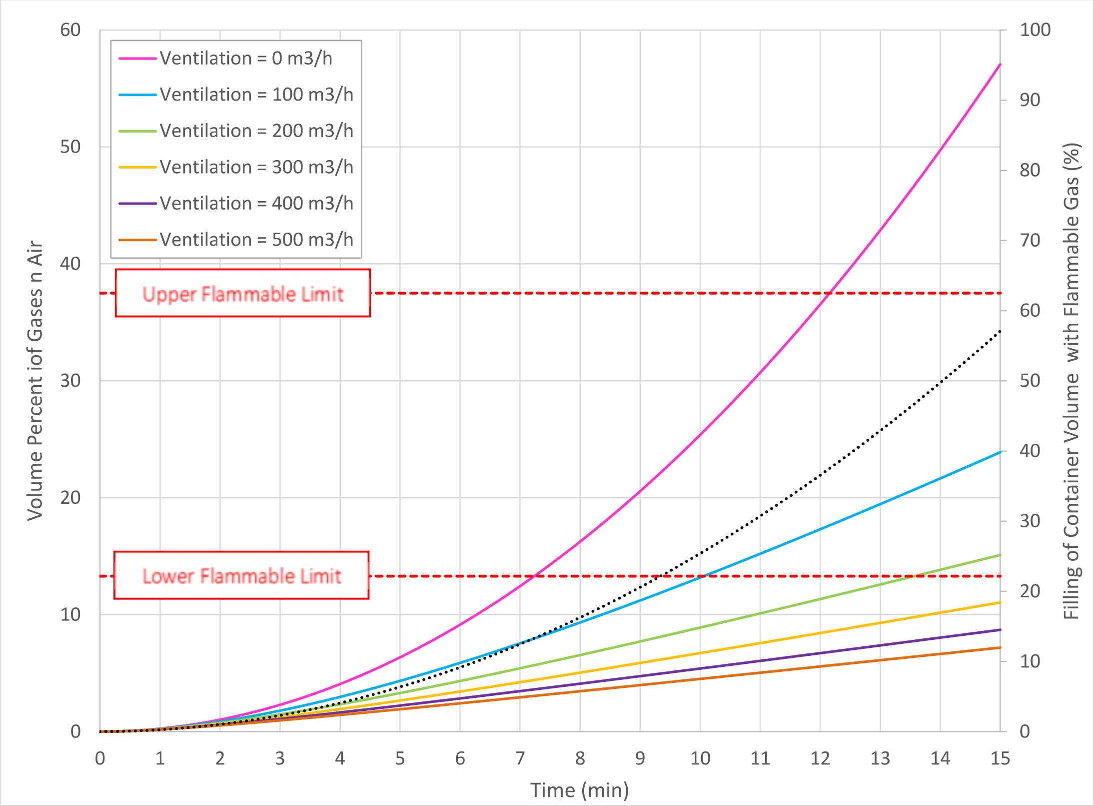


Figure 34 Flammable gas concentration in container for various ventilation rates (parabolic gas discharge profile)

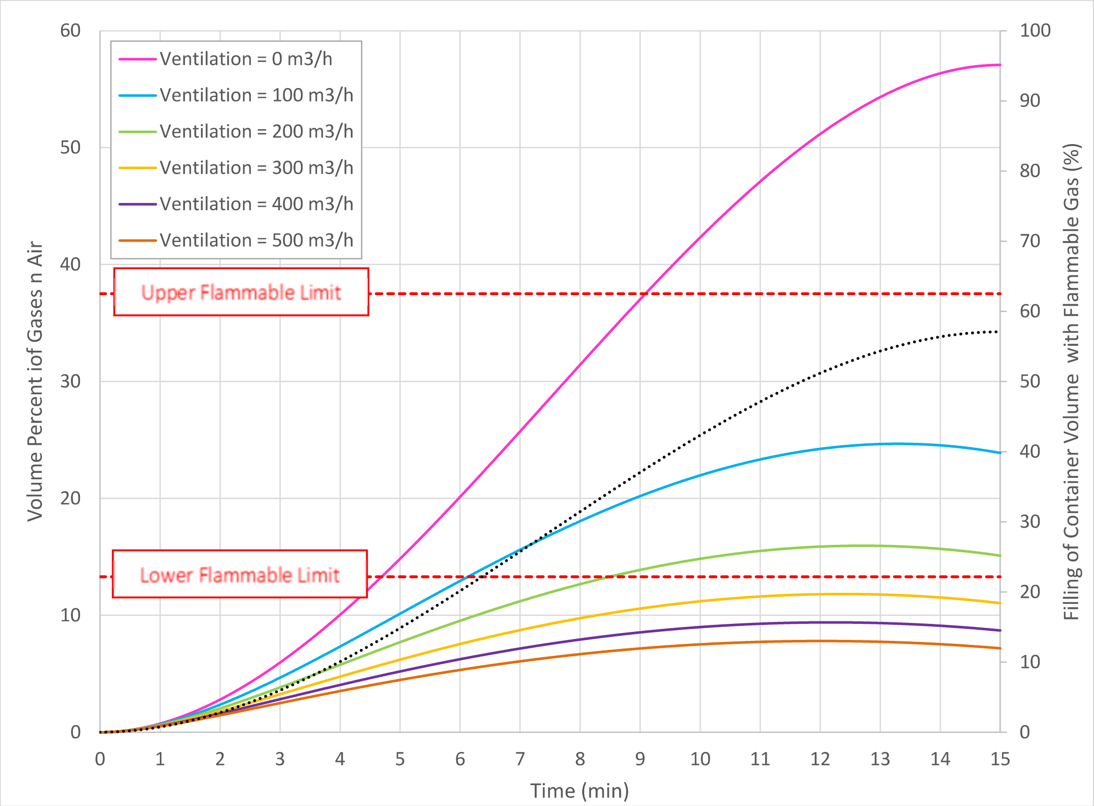


Figure 35 Flammable gas concentration in container for various ventilation rates (half parabolic profile)

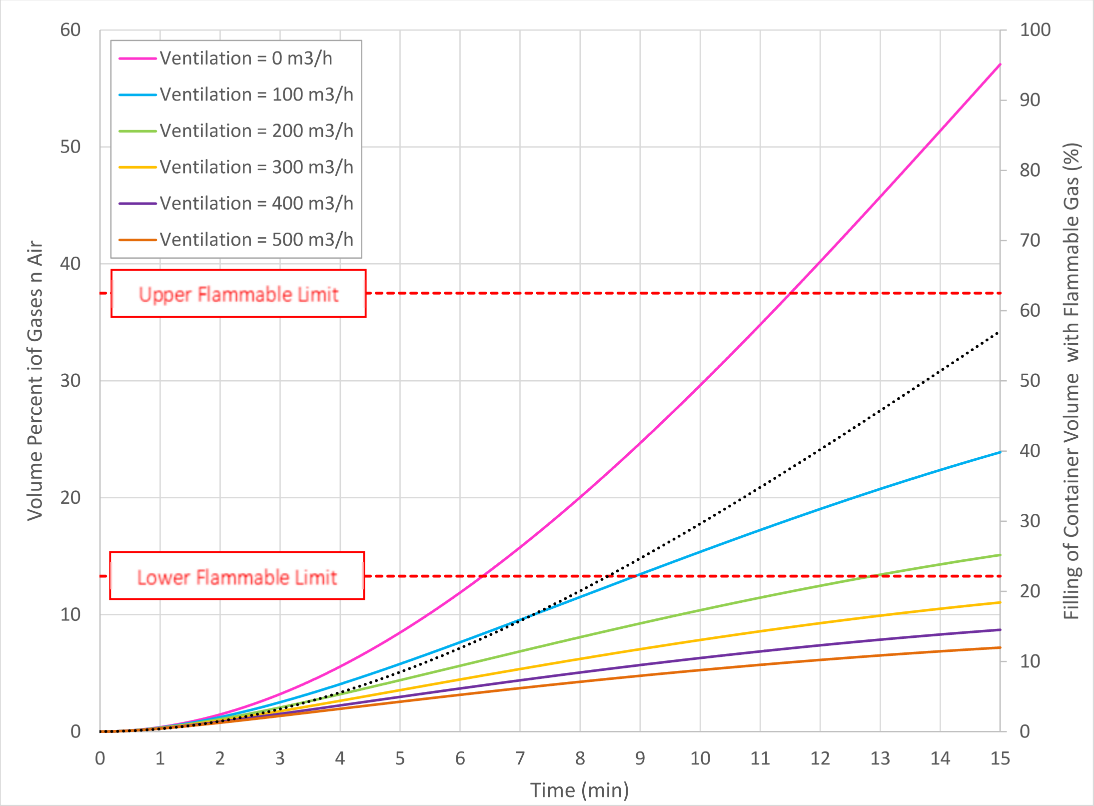


Figure 36 Flammable gas concentration in container for various ventilation rates (Gaussian gas discharge profile)

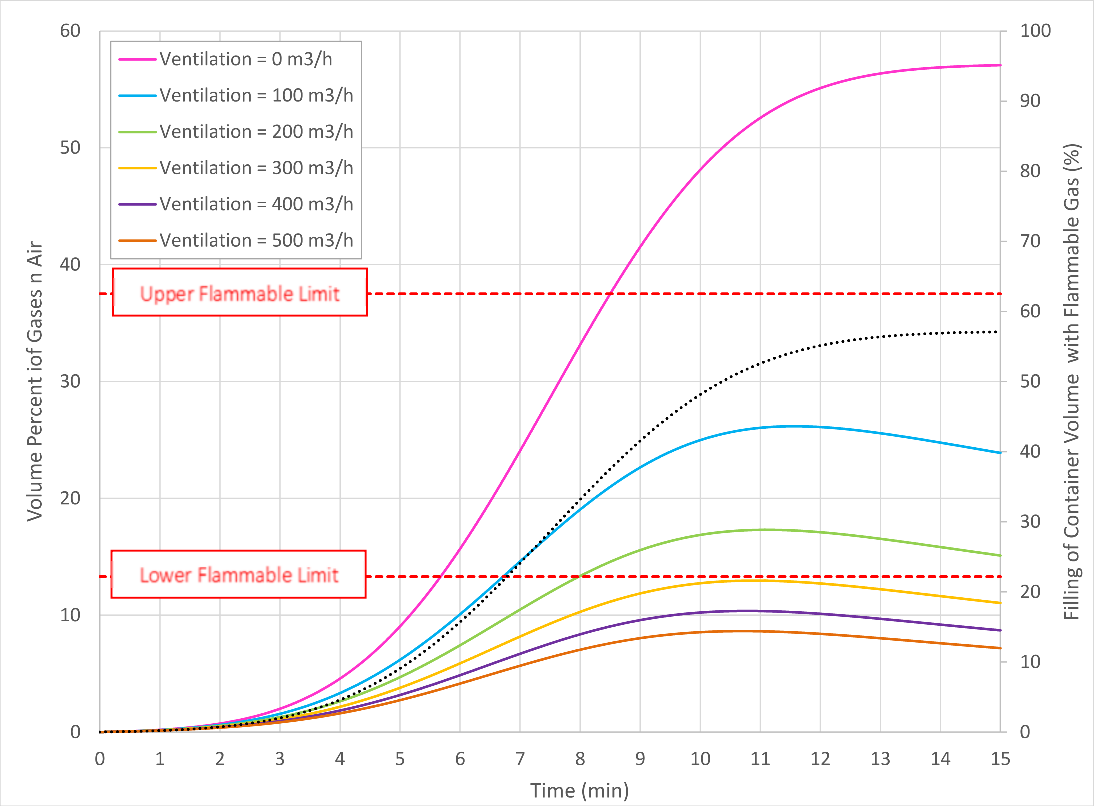
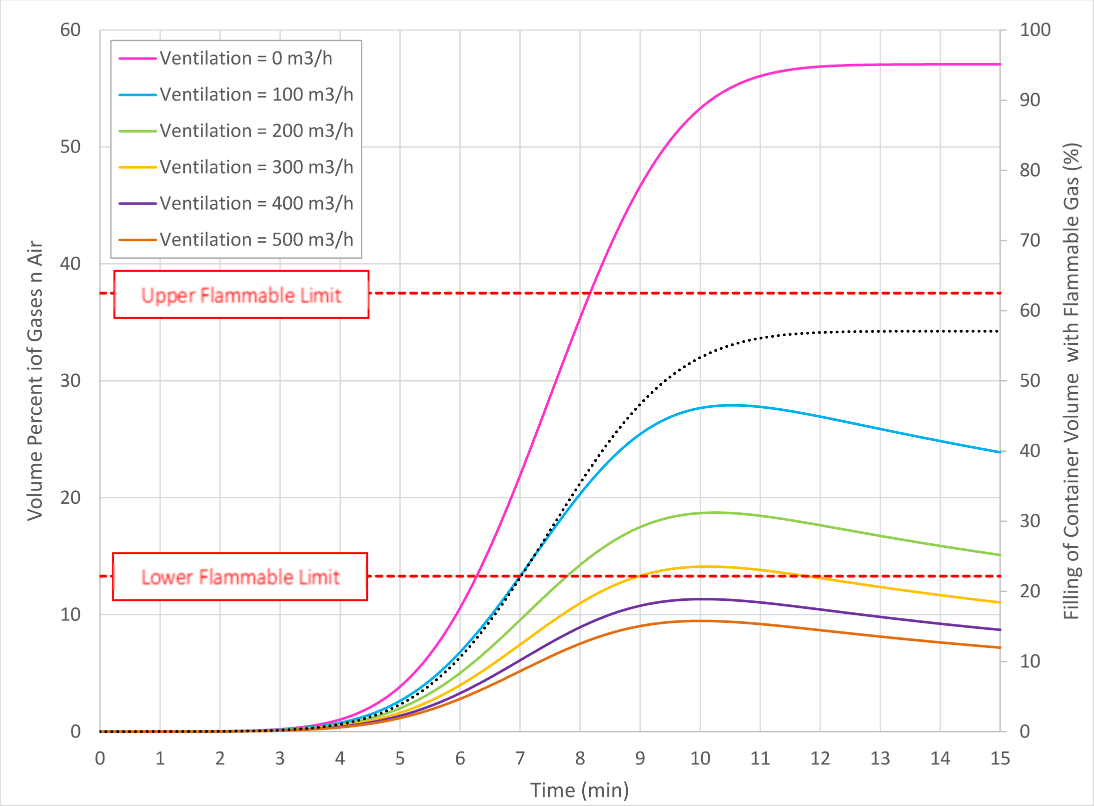


Figure 37 Flammable gas concentration in container for various ventilation rates (Gaussian2 gas discharge profile)



11 Appendix III: Fire Extinguishing Systems for Battery Containers

Several possibilities exist for extinguishing fires in the battery container. These possibilities include:

- Gas extinguishing systems;
- Sprinkler systems;
- Water mist systems.

Gas extinguishing systems

A gas extinguishing system uses inert gasses to reduce the oxygen concentration in the container. This has the following advantages:

- Can suppress a material fire rapidly without causing damage to the battery modules;
- A fully autonomous system;
- No corrosion;
- Individual for each container.

And the following disadvantages:

- Does not provide any or very limited cooling;
- “One-shot” system;
- Extra space inside the container is needed for the gas containers;
- Pressure spike on activation of the system, which may cause structural damage to the container and its apparatus. An adequate pressure release valve is needed.

While this system suppresses the fire inside the container, it will provide limited cooling to a battery module during thermal runaway. The gas inside a nitrogen gas bottle with a volume of 80l and pressure of 300bars can absorb about 6.8MJ of thermal energy. This estimate is equal to the thermal energy of 3 battery cells. The practical use and effective cooling should be tested.

The temperature will continue to rise inside the container and still may cause a full failure of the container. The gasses escaping from the batteries may burn outside of the container, which is an extra fire hazard for the neighboring containers.

Sprinkler system

A sprinkler system sprays water on the heat source from above. This has the following advantages:

- Can suppress fire quickly;
- A fully autonomous system;
- Provides cooling to prevent potential further propagation;
- One global system can cover multiple containers;
- The cooling limits the fire spreading between containers.
- Recommended by NFPA 855 (as far as we now know).

And the following disadvantages:

- In case of failure or a small fire outside the battery modules, the apparatus inside the container may be damaged or corrode;
- A water supply and a pumping system is needed. This needs to be dimensioned to the number of containers in the array;
- Increases the production rate of hydrogen fluoride

When designing sprinkler systems for remote locations, large water storage tanks are needed to provide adequate cooling to cover the time between accident and intervention. The risk analysis of such systems is very dependent on the scale of the ESS array and the environment in which they are installed.

When using a sprinkler system environmental and safety precaution need to be taken in relation to the chemicals inside the batteries. The chemicals will be transported by the fire water and may cause toxic or environmental hazardous liquid solutions. A well-designed sprinkler system might partially save the container provided the battery modules are water resistant. A sprinkler system is best combined with a gas extinguishing system to ensure the material fire is extinguished. A sprinkler system is not an extinguishing system but a suppression system to control the fire.

Water mist system

Analogue to the inert gas extinguishing system, the water mist system creates an inert atmosphere inside the container to suppress the fire. This has the following advantages:

- Can suppress fire quickly;
- A fully autonomous system;
- Provides cooling to the battery module in thermal runaway and the surrounding modules.

And the following disadvantages:

- In case of failure or a small fire outside the battery modules, all the apparatus inside the container may be damaged or corrode;
- “one-shot” system;
- Provides less cooling than a full sprinkler system;
- Increases the production rate of HF.

A standalone water mist system might be a good and cheaper alternative to a sprinkler system but has much less cooling capacity inside the battery packs. This system can be more adequate where quick fire interventions are possible. The production rate of hydrogen fluoride increased when water based extinguishing systems are used. The total amount of HF produced remains the same.

For use of battery containers in remote locations, the use of a CO_2 fire extinguishing system may be the most practical and appropriate.

12 Appendix IV: Summary of HySEA Project

As part of the HySEA project, Gexcon designed a test rig for 20-foot ISO containers and completed 66 vented hydrogen deflagration tests with homogeneous and inhomogeneous mixtures.

The tests with 20 foot ISO containers in the HySEA project were organized in two experimental campaigns and included 42 tests with initially homogeneous and quiescent mixtures:

- 14 tests vented through the container doors.
- 1 test with a closed container.
- 27 tests vented through openings on the roof. 24 tests with inhomogeneous mixtures:
- 17 tests with stratified mixtures.
- 7 tests with initial turbulence generated by either a fan or a transient jet.

The total number of tests was 72, including five unignited tests and one failed test. *Figure 38* shows selected frames from test 61. Figure 5 compares the maximum explosion pressures measured inside the container for 30 of the 66 tests with predictions according to the European standard EN 14994 (2007) for explosion venting protective systems.

The empirical correlations in EN 14994 are only applicable for empty enclosures and flammable atmospheres with gas explosion constants $K_G < 550$ bar $m \cdot s^{-1}$, corresponding to the reactivity of hydrogen-air mixtures with concentrations in the range 22-28 vol% hydrogen. Hence, the model predictions indicated in Figure 39 were obtained using published values for the maximum rate of pressure rise and the maximum explosion pressure from a 6 liter explosion vessel as input to the commercial software package WinVent 4.0.

Figure 40 shows examples of empirical pressure-impulse (P-I) diagrams for 20 foot shipping containers, where the damage criteria, i.e. the P-I curves, are based on specific levels of permanent deformation, as well as whether the containers were damaged beyond repair. The plot on the left resembles a classical P-I diagram for ideal blast waves while the plot on the right illustrates how the P-I curves can be modified to account for the effect of the finite rise time of the pressure loads.

From the point of view of vented deflagrations, 20 foot ISO containers are relatively weak structures, and the structural response measurements reveal significant deflection of the container walls even for relatively modest pressure loads. Hence, the volume of the enclosures varied significantly during some of the tests, especially the more violent explosions. The vent panel opened simultaneously in most of the tests with commercial panels. The main structure of the container remained intact in all tests, except from test 9 where the hinges broke when the doors opened. One door bounced off the gravel on the side of the container, hit the hillside some 10 m above the ground, and landed about 30 m from the container. This observation demonstrates the hazard posed by projectiles and highlights the importance of securing attached structural elements such as doors, louvre panels and ventilators.

The container doors do not represent proper explosion venting devices according to the European standard (EN 14797, 2006). The containers walls ruptured in some of the tests that produced high overpressures, e.g. test 9 in Figure 39. This figure also illustrates that the maximum reduced explosion pressures increase consistently with increasing fuel concentration for all obstacle and vent configurations. This is reasonable since most tests involved lean mixtures, i.e. less than 30 vol% hydrogen in air. Tests 34 and 69 with rich mixtures (42 vol% hydrogen) were included to explore near worst-case conditions for a modest degree of congestion (P2). The maximum pressures increase more rapidly for tests with internal congestion, compared to the predictions by EN 14994 (2007).

The results for tests 71 and 72 demonstrate the strong effect that higher levels of congestion (HC) can have on the maximum reduced explosion pressure, even for a modest increase in concentration (from 12 to 15 vol.%) for lean hydrogen-air mixtures.

Figure 38 Explosion test in a 20 foot ISO container as part of the HySEA project (FABIG, 2019)

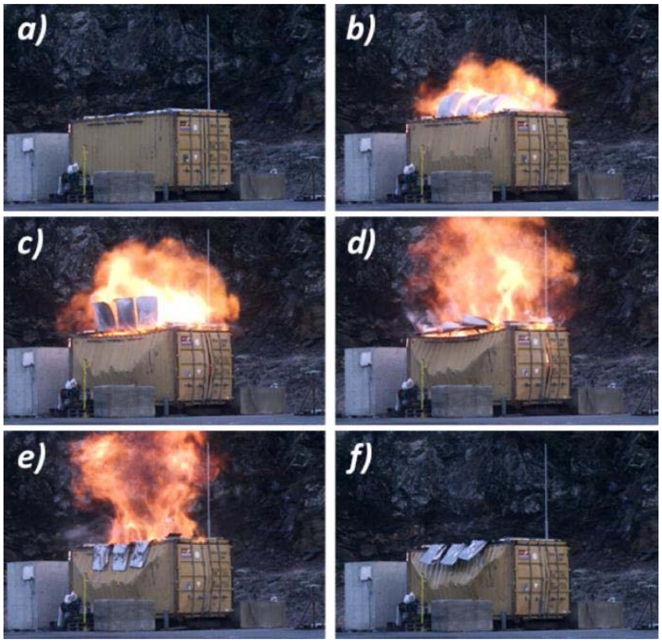


Figure 39 Results of hydrogen explosion testing in a 20 foot ISO container (FABIG, 2019)

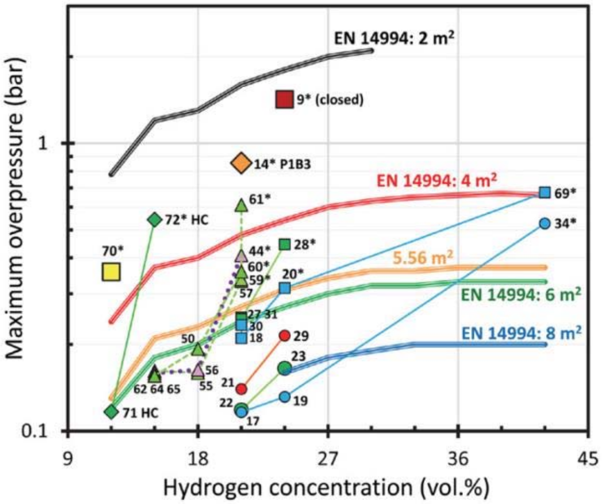
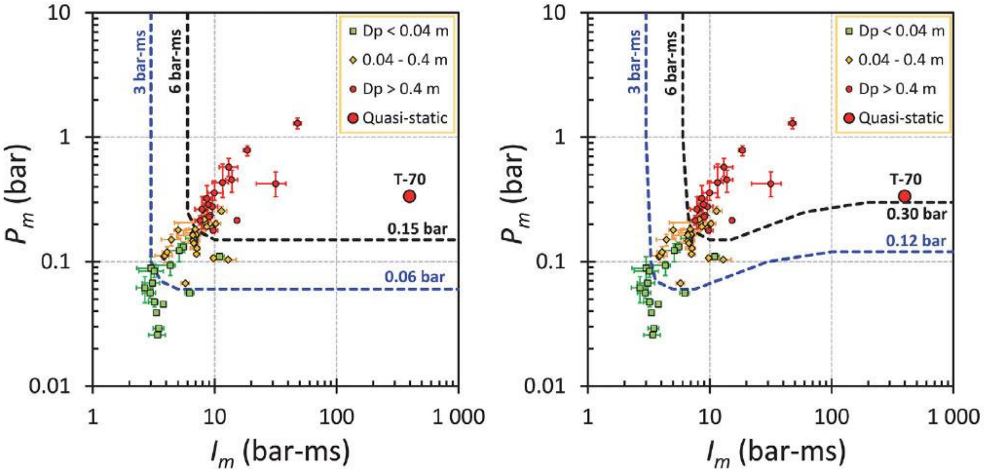


Figure 40 Response of 20 foot ISO container to hydrogen explosions (FABIG, 2019)



13 Appendix V: Heat Radiation from Vented Gases in Container

Figure 41 Heat radiation results for thermal runaway of all batteries in 5 minutes

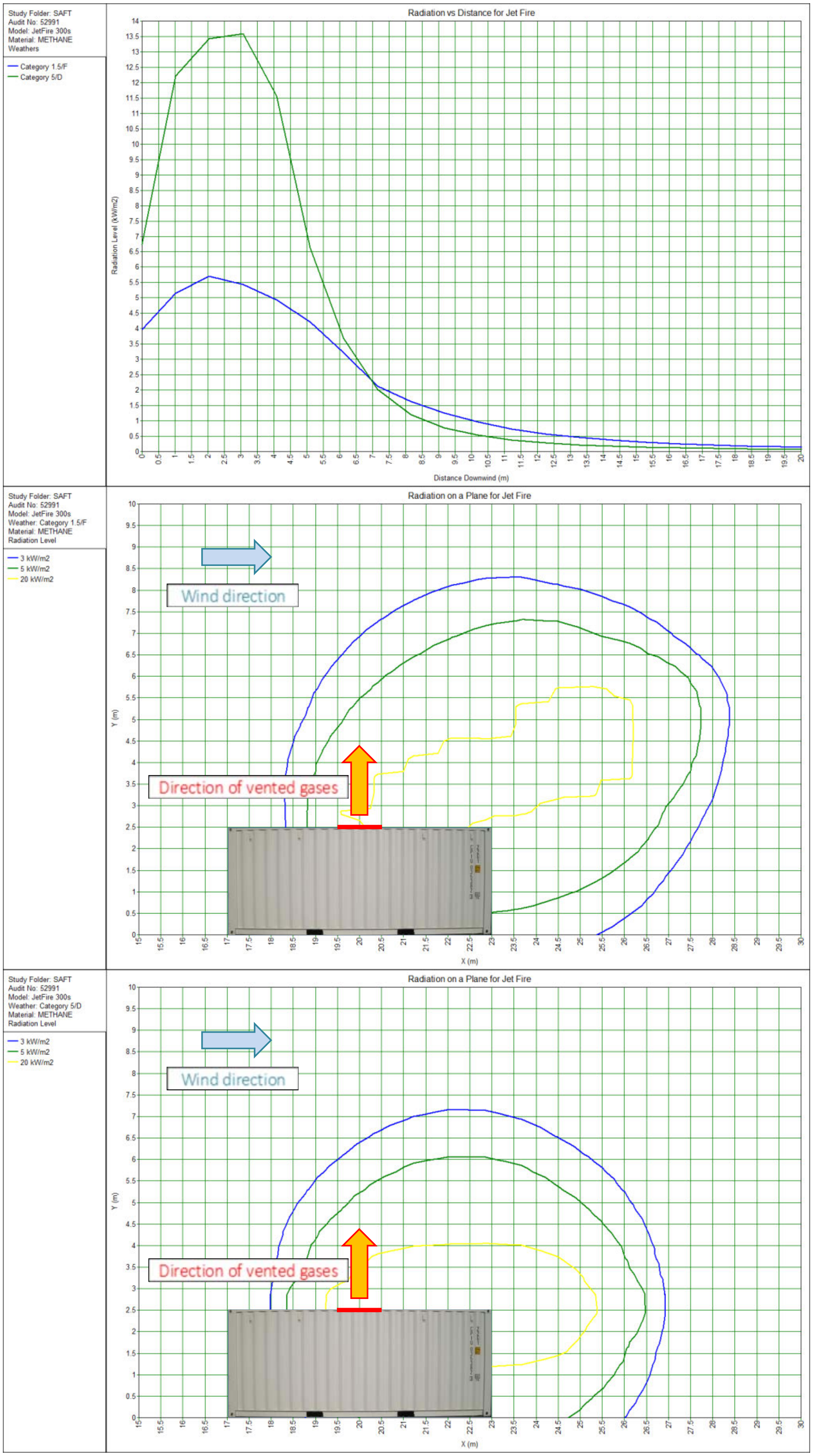


Figure 42 Heat radiation results for thermal runaway of all batteries in 10 minutes

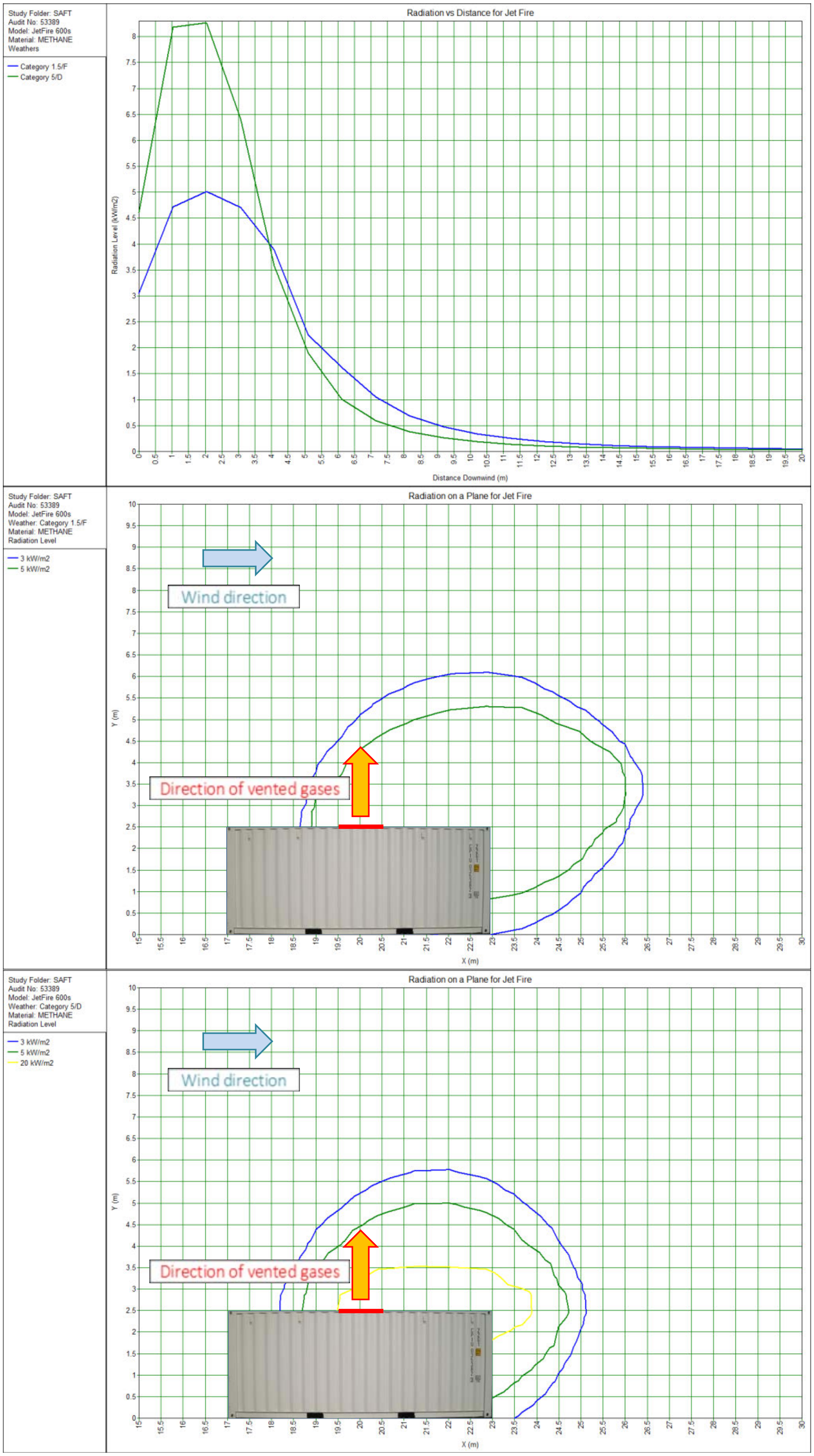
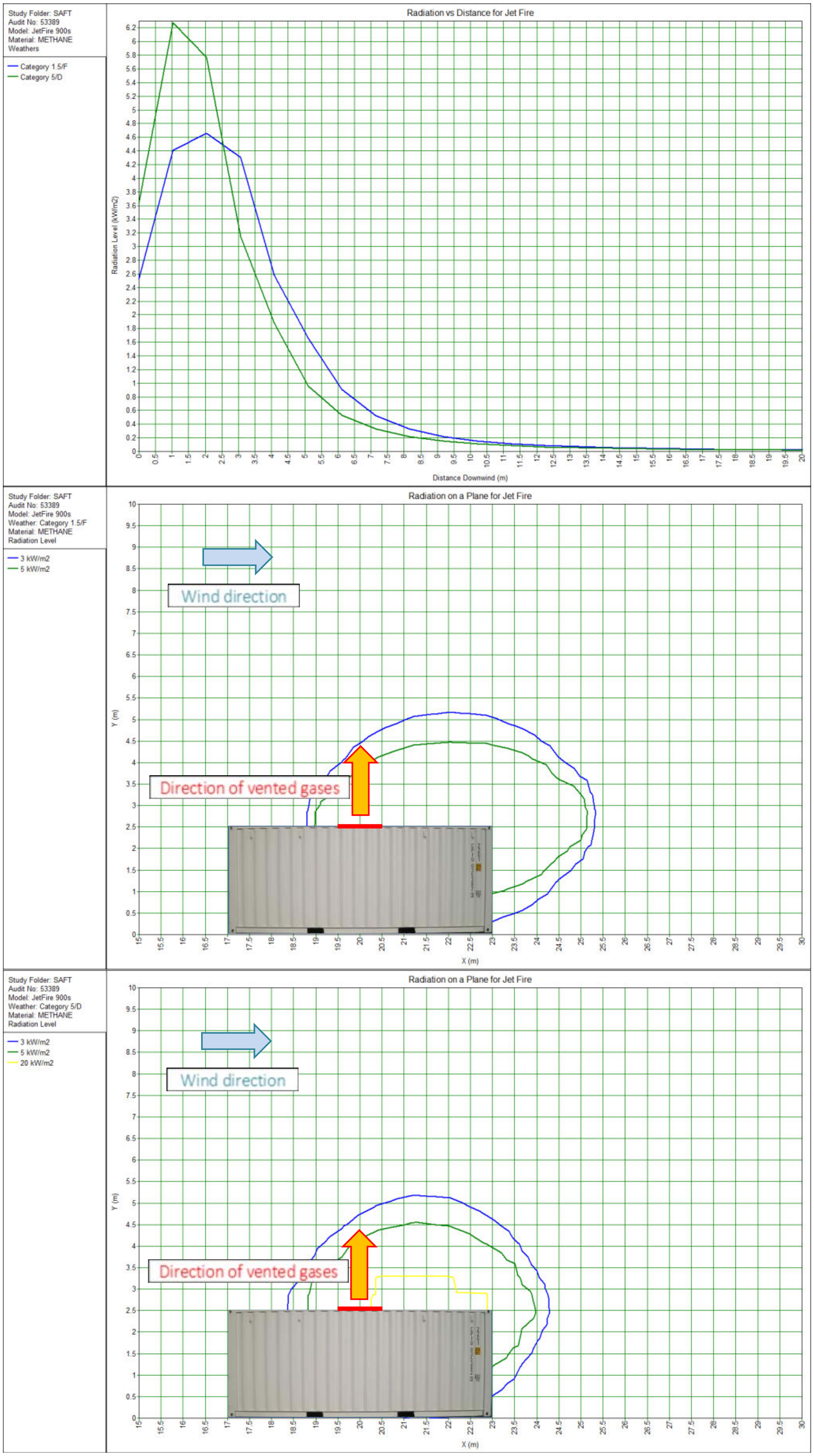


Figure 43 Heat radiation results for thermal runaway of all batteries in 15 minutes



14 Appendix VI: Toxic Dispersion from Vented Gases in Container

Figure 44 Toxic gas dispersion results for thermal runaway of all batteries in 5 minutes

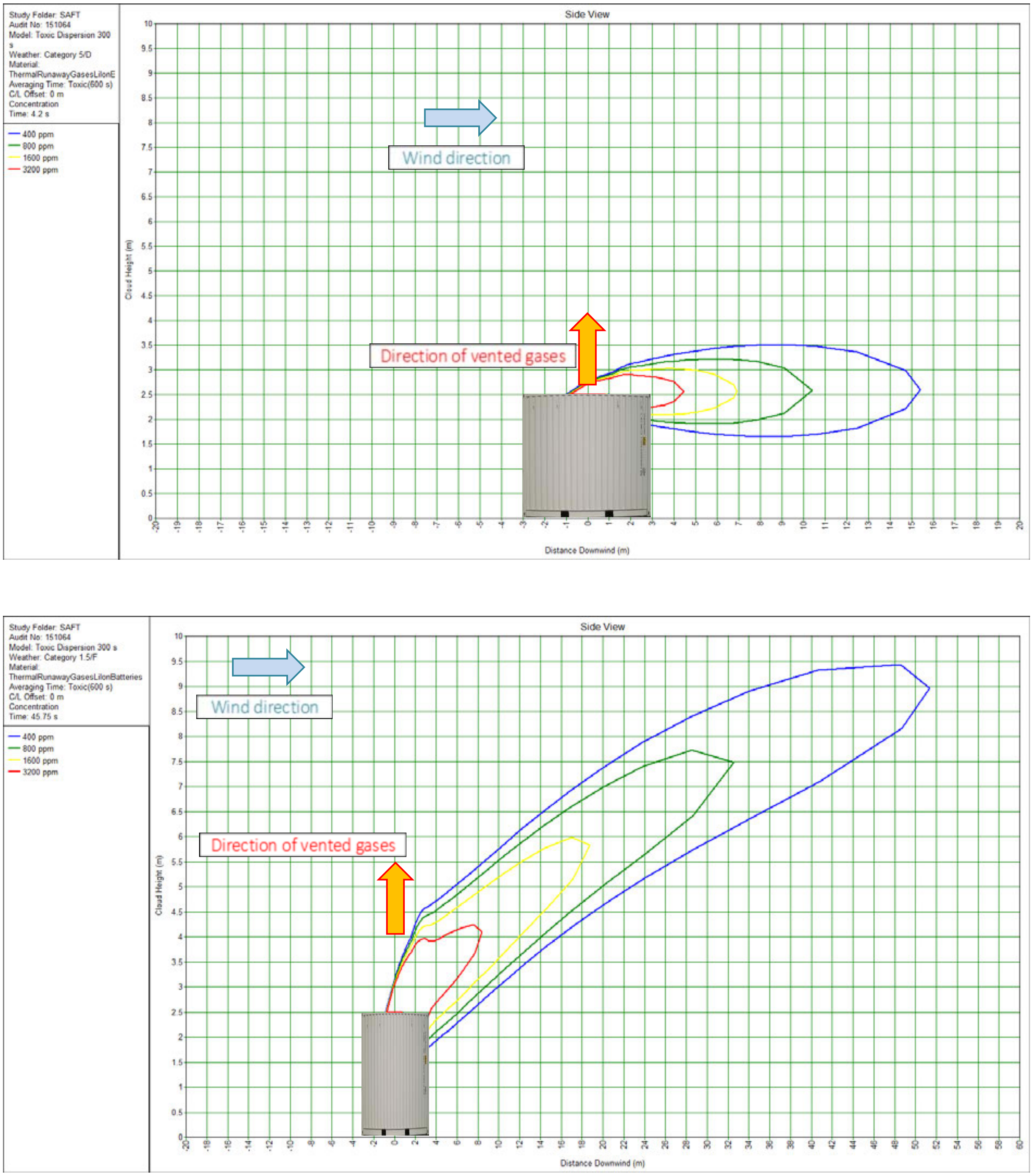


Figure 45 Toxic gas dispersion results for thermal runaway of all batteries in 10 minutes

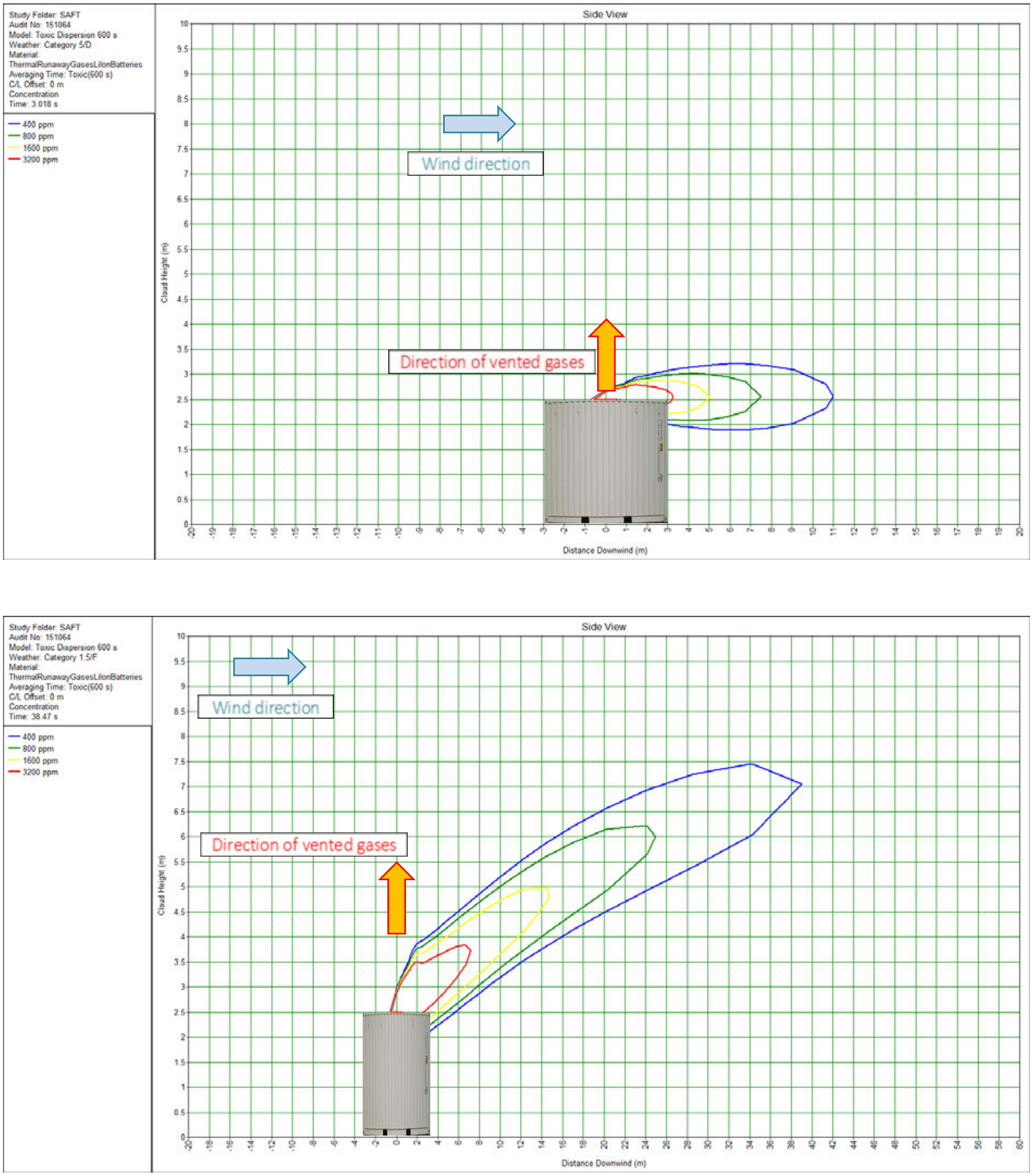
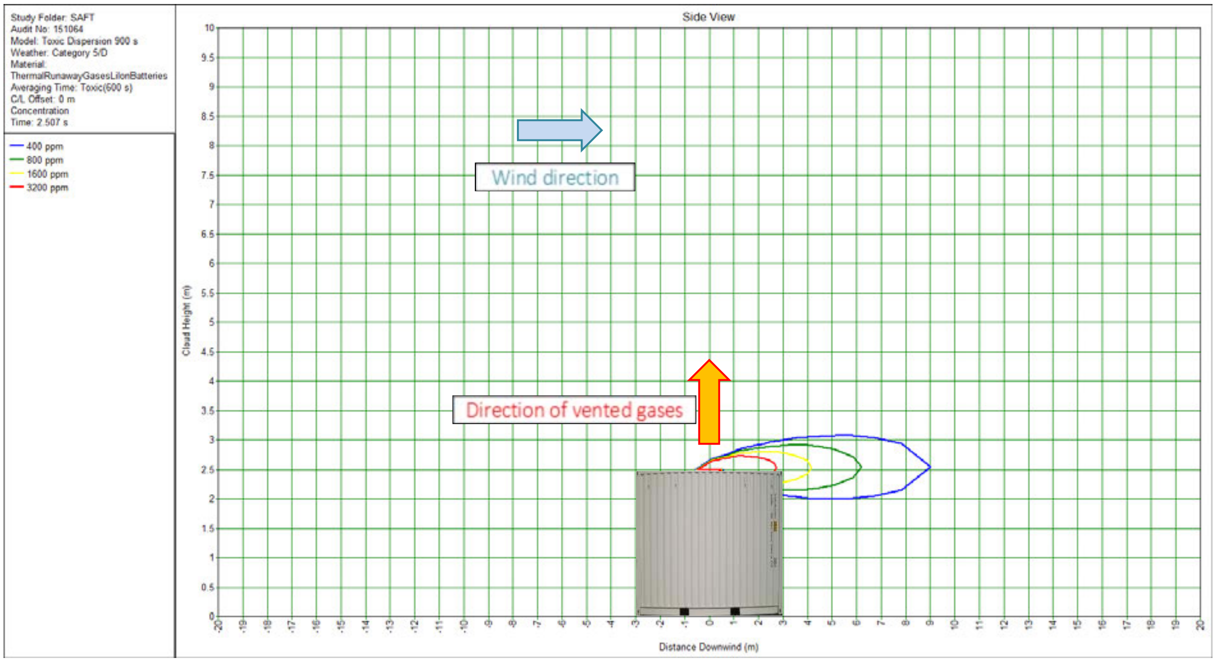


Figure 46 Toxic gas dispersion results for thermal runaway of all batteries in 15 minutes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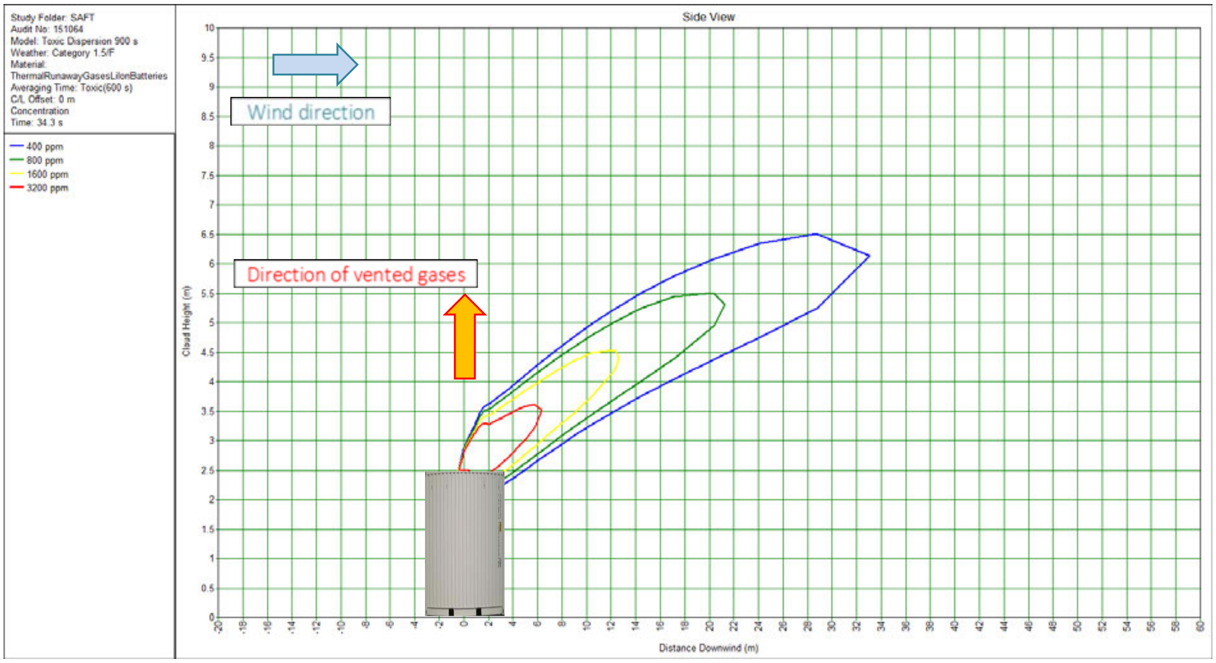
Audit No: 151064
Model: Toxic Dispersion 900 s
Weather: Category 5/D
Material:
ThermalRunawayGasesLiIonBatteries
Averaging Time: Toxic(600 s)
C/L Offset: 0 m
Concentration
Time: 2.507 s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Audit No: 151064
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Weather: Category 1.5/F
Material:
ThermalRunawayGasesLiIonBatteries
Averaging Time: Toxic(600 s)
C/L Offset: 0 m
Concentration
Time: 34.3 s

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ACCURE
Battery Intelligence

Predictive diagnostics to improve battery safety

WHITE PAPER

Predictive diagnostics to improve battery safety

Lithium-ion batteries (LIB) are a key enabler of our clean energy future. Today, LIB already power devices from electric scooters to ships and grid-connected storage systems. However, as with all energy sources, batteries carry a certain risk of failure. For LIB this can result in gassing and burning, potentially harming people and property. The ongoing trend towards ever higher energy densities literally adds fuel to the fire.

Figure 1 shows the trade-offs typically made in the design of LIB. To achieve higher energy densities, manufacturers use more reactive materials while minimizing safety margins. With more energy stored in a single battery, larger amounts of energy are released in case of a failure.

With the fast growth of the battery industry, the number of battery incidents has also increased. One prominent example is the 2019 fire at an APS site in McMicken, Arizona. A battery failure led to a massive explosion in one of the storage containers, causing millions in damages and hospitalizing several firefighters. In the automotive world, General Motors, Hyundai, and Kia had to recall over 200,000 electric vehicles between 2020 and 2021 after more than 30 battery fires. All these incidents involved world leading companies with decades of experience in the battery sector.

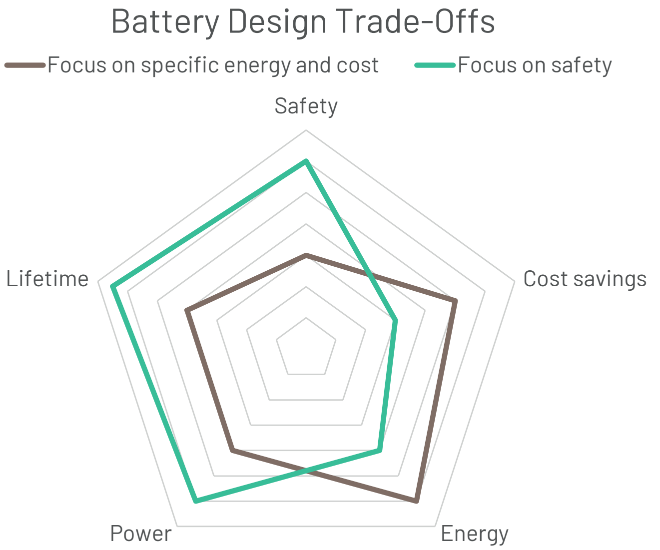

Figure 1: Illustration of the typical trade-offs in battery cell design

1. Types of battery faults

Critical battery incidents include cell openings that lead to the release of toxic gasses (including hydrofluoric acid), internal short circuits and fires. Once a LIB ignites, it becomes practically impossible to extinguish the fire, as the decomposition of its active materials generates oxygen, continuously fuelling the fire – the dreaded thermal runaway. A major thread lies in the fact that once a cell goes into thermal runaway, the incident can easily cascade into neighbouring cells, ultimately destroying the whole storage system and/or adjacent facilities.

Figure 2 illustrates the causes, cell internal processes, and resulting failure mechanisms of a battery system. One of the main root causes of battery faults are **manufacturing defects**. These can occur on cell, module, or system level.

- Common problems on **cell level** include contamination of materials, inhomogeneities in the production process or insufficient safety margins. General Motors stated in late 2021 that internal investigations of the series of Chevrolet Bolt fires suggest a torn anode tab and a folded separator to be the root cause.
- On **module level**, poor cell connections, a faulty thermal management or a mismatch of the cells can cause safety issues. Semi- or even fully automated welding for instance, does not only apply a short but distinct thermal stress to the battery cells, but also brings along a specific failure rate. With millions of cells being assembled into modules each day, even thorough QM procedures sometimes miss these errors.
- On **system level**, a bad coordination of multiple battery modules or faulty state estimation can start a devastating error chain. Errors on system level like these are likely the reason for a significant part of the docents of fires in large-scale battery storage systems in South Korea between 2018 and 2019.

Additional danger can come from **operational faults**. LIBs are designed to work within a clearly specified range of boundary conditions regarding temperature, voltage and current. Operating a LIB outside of these limits does not only cause accelerated aging but can trigger critical failure mechanisms like a thermal runaway. While every LIB is equipped with a battery management system (BMS) that is responsible for keeping the battery in a safe operating range, reality has shown that even BMS from world-leading suppliers can fail – with sometimes devastating effects (see next chapter).

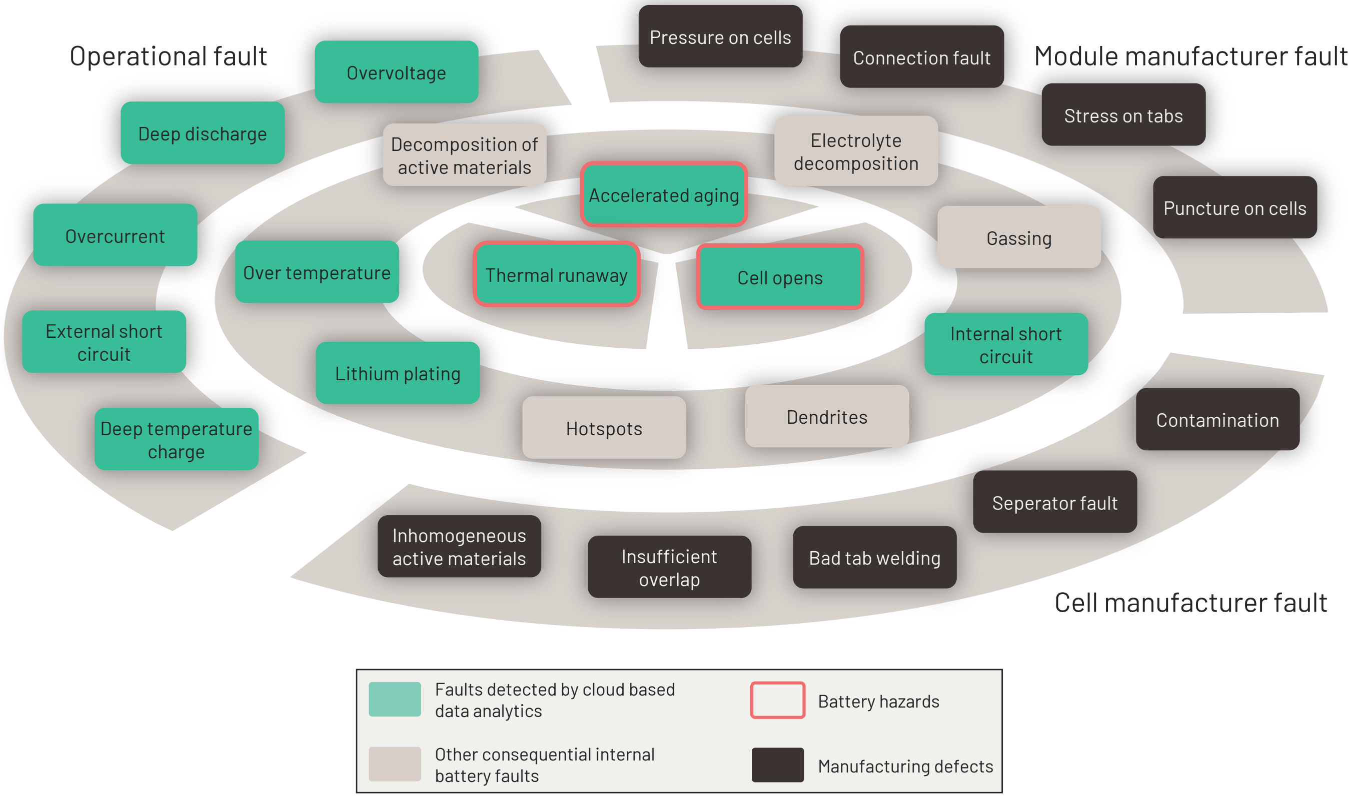

Figure 2: Illustration of root causes of battery failures (outer circle), cell internal processes (intermediate circle) and eventually resulting failure mechanisms (inner circle).

2. Battery protection measures and fault diagnostics

Well-designed LIBs always come with multiple layers of protective measures to ensure a safe operation. The most important protection measures are presented in the following.

2.1 Passive Safety Features

LIB systems usually contain several passive components to ensure the safety of the overall system, including:

- Fuses and relays that break circuits at high currents or in case of failures
- Vents that let out gasses to release pressure from the cell [1]
- Current Interrupt Devices (CID) that interrupt the current path if the internal pressure of a cell exceeds a predefined level
- Positive Thermal Coefficient (PTC) thermistors that reduce the current at high battery temperatures
- Thermal insulation materials such as mica sheets to limit thermal propagation
- Fire-proof housings which can contain a fire inside a battery module, although toxic gas is still released

However, passive safety components are last resorts to minimize the damage from critical situations that are already happening – in many cases they cannot prevent them.

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[1] The released toxic gasses, however, can contaminate facilities or be blown into residential areas.

2.2 Battery Management Systems

Battery management systems (BMS) are electronic circuits containing sensors, logical units, actors, and a communication interface. BMS make sure that a battery is operated within its specifications and usually cover the following tasks:

- Continuously monitor the voltage, current and temperature of the battery system via sensor measurements
- Estimate values such as state of charge (SOC), state of power (SOP) and state of health (SOH)[2]
- Perform active or passive cell balancing to ensure that all battery cells are working at the same SOC
- Communicate with other parts of the overall system (e.g. inverters and energy management system) to ensure smooth operation

While BMS are crucial to the safety of LIB, they also have noticeable shortcomings:

They only see the cells within the corresponding battery pack, have little to no access to historic data or data from other battery systems and are limited in their computing power. Due to these limitations, their capability of detecting anomalies or analysing long-term trends are usually slim to none.

2.3 Predictive diagnostics

An effective strategy to improve battery safety in mobility and energy applications is the use of predictive diagnostics. By detecting critical faults at an early stage, battery operators can act before any damage is done. As the diagnostics are solely based on existing data streams, they can be applied to any LIB system without the need for any product modification. The concept of predictive diagnostics is presented in **Figure 3** and summarized in the following.

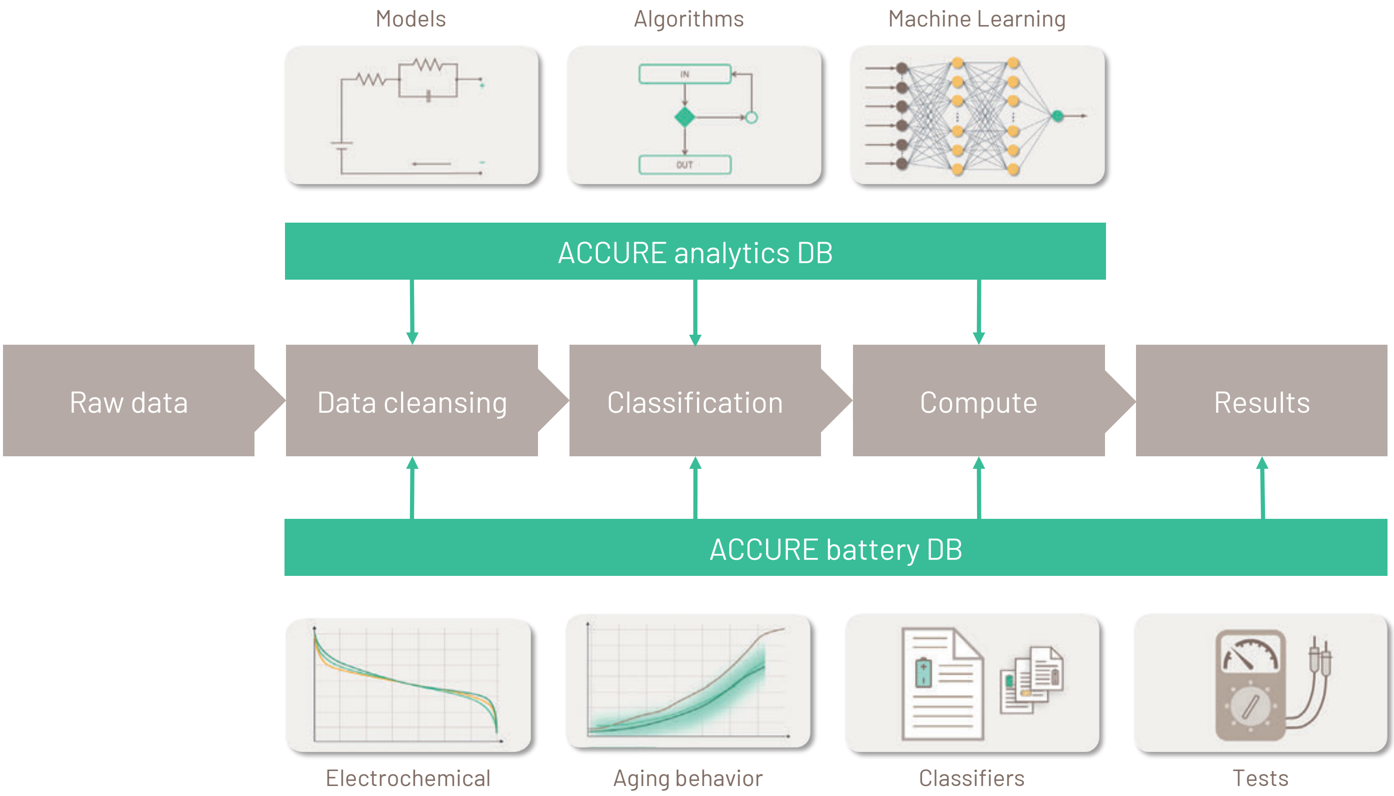

Figure 3: Schematic workflow of ACCURE's predictive diagnostics

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[2] Due to the limited computing capabilities of BMS, these estimations can be bad. As an example, Tesla faced severe trouble with their Chinese Model 3 cars due to bad SOC estimations. The batteries regularly went into deep discharge, permanently damaging the batteries.

Step 1: Data pre-processing

The starting point for all calculations is the continuous stream of measurements coming from the BMS ("raw data"). To leverage this data, extensive data cleansing needs to be performed: For one, outliers and systematic measurement errors need to be detected and flagged as such to avoid false interpretations. But more generally speaking, every BMS has its own (systematic and statistical) errors and idiosyncrasies that need to be understood to make sense of the data. A robust cloud platform must be able to work with any kind of input data and needs to draw the right conclusions from every new data point.

Step 2: Fault detection

Fault detection algorithms scrutinize the battery data to check for potential faults. A fault can be identified through changes in primary parameters such as voltage, temperature and current or in secondary parameters such as impedance, a shift in the open circuit voltage curve or the amount of active lithium in each cell. To track secondary parameters, model-based algorithms, which consider reduced order physical-/chemical processes through mathematical equations are used. Identifying and tracking specific patterns in these parameters for the millions of similar cells, which are in operation, enables these algorithms to find anomalies before they become dangerous.

Step 3: Reporting

If a battery is identified to be dangerous, automatic warnings are generated. A two-level system has proven to be effective in this regard.

- Yellow warnings indicate that a battery is experiencing systematic underperformance or showing unexpected behaviour – for example due to a miscalibration of the BMS or a loose cell connector. These issues can oftentimes be resolved by a technician or a software update before they become problematic.
- Red warnings require immediate action, as a critical fault is imminent. The battery system should be brought into a safe operational state and needs to be investigated or replaced by a trained expert.

3. Examples of predictive diagnostics

With hundred thousands of battery modules under management, ACCURE Battery Intelligence operates one of the largest battery databases in the world – including systems that experienced critical failures. Four examples of such systems are presented below. To protect the interests of our partners, all results are anonymized and slightly modified while preserving all relevant information.

BMS failure detection

It is the BMS's job to supervise the battery cells, but who supervises the BMS? Most BMS do not provide full redundancy. Hence, failures are not likely, but do occur and can result in devastating failures. **Figure 4** shows the voltage profile of a battery cell from a top-5 battery supplier.

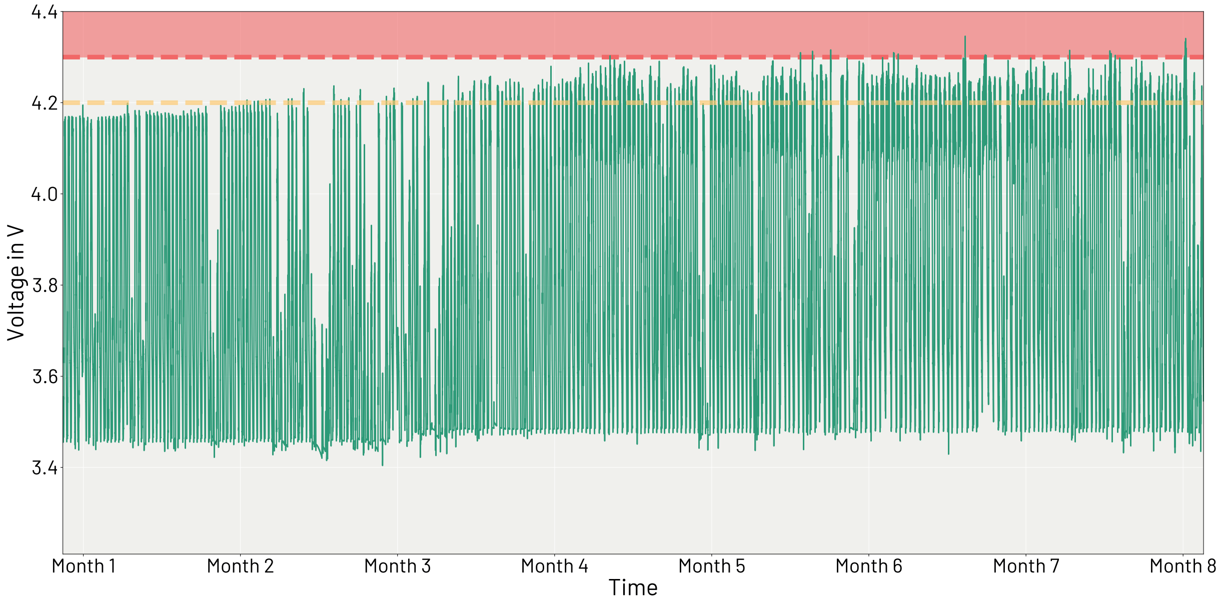

Figure 4: End-of-charge voltage increases over time causing voltages to reach critical values

The full charge voltage of this battery steadily increases over time, way beyond its specifications. Such overcharging not only causes accelerated aging but can also drive lithium-ion batteries into a thermal runaway. An online safety monitoring can reliably catch BMS shortcomings like these before they trigger critical battery failures.

Drifts between cell voltages

Whenever battery cells are connected in a serial configuration it is advisable to implement a balancing system. The balancing system levels the SOC of the individual cells to maximize the usable energy content. Accordingly, in normal operation, the voltage of the cells should be identical throughout a large SOC range. Persistent voltage drifts can be precursors for cell faults, which could lead to gassing and/or fires. **Figure 5** shows the voltage drift over time for a faulty battery module.

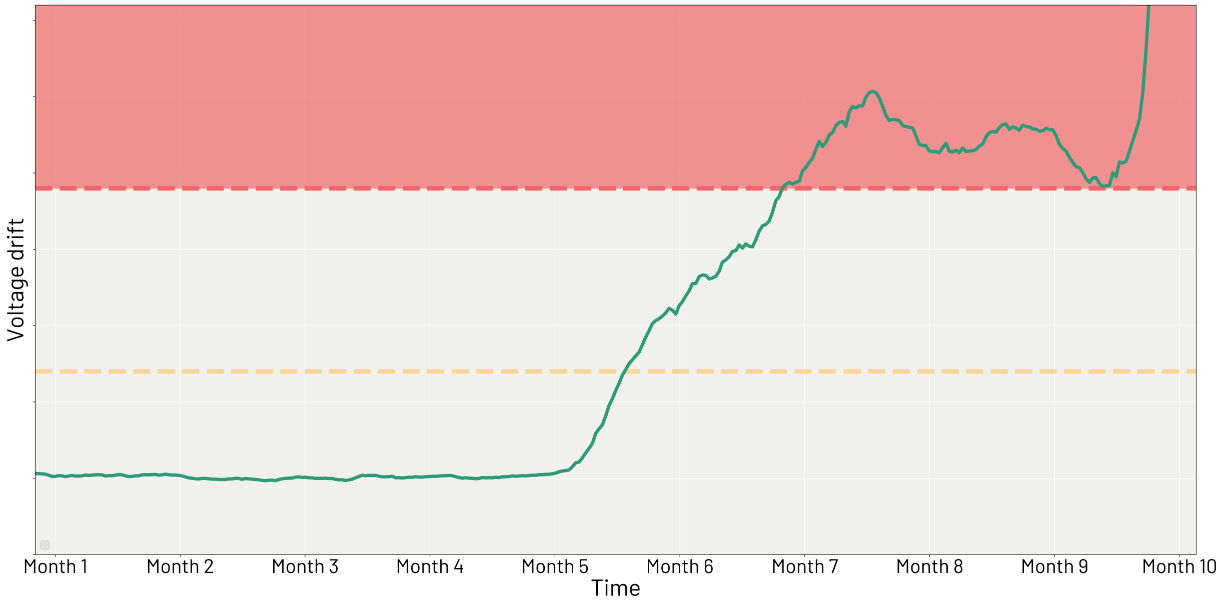

Figure 5: Voltage drift between battery cells exceeds acceptable limits, indicating a failure

The accelerated voltage drift starting between month 5 and 6 is a strong indicator for a battery cell failure. Eventually, the voltage drift reaches a critical level. ACCURE's safety algorithms automatically warn about such irregular battery behavior.

Model-based safety diagnostics

An advanced and powerful way of tracking battery safety is via model-based approaches. These algorithms mirror electrochemical relationships and processes, thus revealing information about the internal states of the battery. One example for a LIB model parameter extracted from operational data is presented in **Figure 6**.

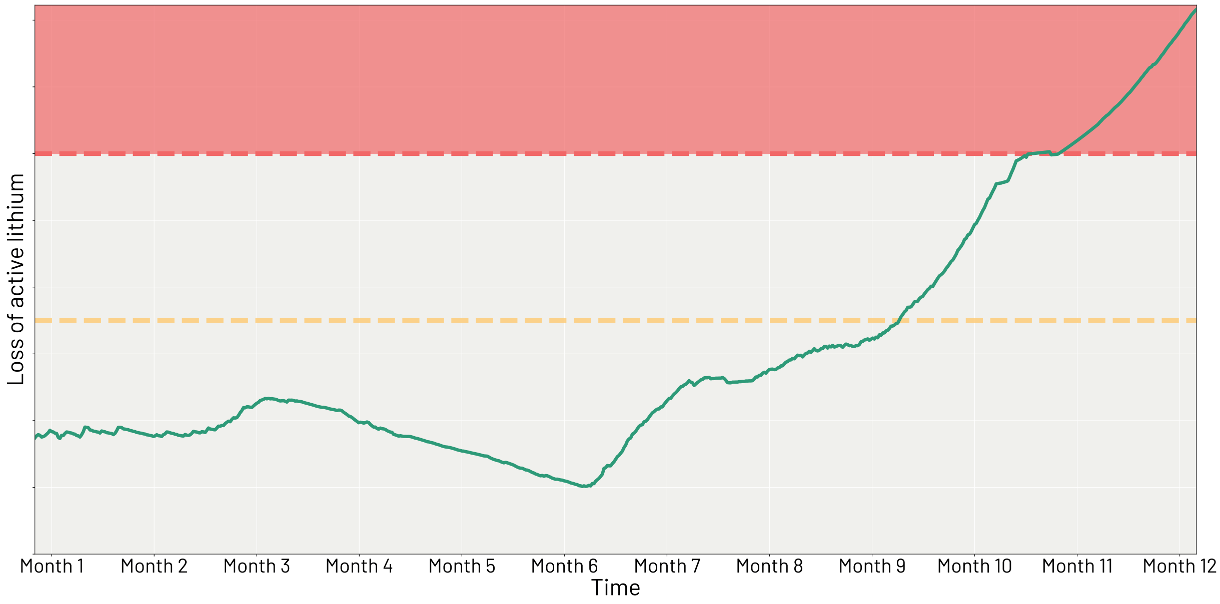

Figure 6: Model-based safety diagnostics track the loss of active lithium over time

If a battery is charged with comparably high current rates, possibly at low temperatures, lithium-plating may occur. Lithium-plating does not only age the cell, but it can also become a safety threat by forming metallic dendrites and triggering side reactions such as gassing. It manifests itself in a decrease of the lithium inventory which is no longer available for the main reaction. ACCURE's safety algorithms closely track the loss of active lithium in battery cells to predict safety critical events.

4. Conclusion

To be a key pillar of our energy and mobility world, batteries must be safe and reliable. Predictive diagnostics have proven to be an effective extra layer of safety that can be implemented without the need for additional hardware or product modifications. This also enables **smart insurance products**, which ACCURE is offering together with international partners.

ACCURE
Battery Intelligence

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Appendix B Proposed Fee Schedule for Discharge of Requirements

Fees

(1) Where an application is made to the relevant authority for consent, agreement, or approval in respect of a requirement, a fee shall be paid to that relevant authority as follows —

Requirement	*Fee*
Category 1: Design approval – first application Requirement 6: Detailed design approval – first application to each relevant planning authority Requirement 11: Fencing and other means of enclosure – first application to each relevant planning authority Requirement 12: Surface and foul water drainage – first application to each relevant county authority Requirement 21: Permissive paths – first application to each relevant planning authority Requirement 22: Decommissioning and restoration – first application to each relevant planning authority	£2,028
Category 2: Design approval – subsequent applications Requirement 6: Detailed design approval – subsequent applications to each relevant planning authority (following a Category 1 submission) Requirement 11: Fencing and other means of enclosure – subsequent applications to each relevant planning authority (following a Category 1 submission) Requirement 12: Surface and foul water drainage – subsequent applications to each relevant county authority (following a Category 1 submission) Requirement 21: Permissive paths – subsequent applications to each relevant planning authority (following a Category 1 submission) Requirement 22: Decommissioning and restoration – subsequent applications to each relevant planning authority (following a Category 1 submission)	£462
Category 3a: re-approvals for Category 1 and 2, and under Requirement 5 (i) In respect of any Category 1 or Category 2 requirement where an application is made for discharge in respect of which an application has been made previously; and (ii) Requirement 5: Approved details and amendments to them	£462
Category 3b: re-approvals for Category 4 In respect of re-approvals of matters previously approved under Category 4.	£116
Category 4: Other Requirement 3: Phasing of the authorised development and date of final commissioning Requirement 7: Fire safety management	£116

Requirement 8: Landscape and ecology management plan Requirement 10: Stone curlew Requirement 13: Archaeology Requirement 14: Construction environment management plan Requirement 15: Operational environment management plan Requirement 16: Construction traffic management plan Requirement 17: Operational noise Requirement 18: Ground conditions Requirement 19: Water management plan Requirement 20: Skills, supply chain and employment	

Refund of fees

2) Any fee paid under this Schedule shall be refunded to the undertaker within if the relevant authority failing to determine the application within the timescales set out Article 2(1) of Schedule 13 of the DCO.

Appendix C Table of Site Access Requirements

Table of Site Access Requirements – Appendix to EXQ3.9.9

Site Access	**Existing Use**	**Construction Use**	**Operation Use**	**Decommissioning Use**
Sunnica West Site A: Site Access A on La Hogue Road	• 3.5m wide farm access packed gravel and dirt used by agricultural vehicles. • Provides access to agricultural land and farm buildings. i) the right at all times to use all Access Roads within the Property ii) right of entry with or without machinery and equipment to woodland areas on the Property to thin and remove timber iii) right of entry to connect and draw water from hydrants • RoA for Environment Agency to access equipment adjacent to A11 (grid ref TL673668). Reactive maintenance required; however, main access will likely be from A11	• Main access to construction car park. • No requirement to serve agricultural use. • Right of access to farm buildings, as existing. • RoA for EA as existing	• Right of access to farm buildings i) the right at all times to use all Access Roads within the Property ii) right of entry with or without machinery and equipment to woodland areas on the Property to thin and remove timber iii) right of entry to connect and draw water from hydrants • RoA for EA as existing • No requirement to serve agricultural use. • To be used as main access to operational car park. • Limited maintenance requirement for PV array, comprising occasional small level of LGV movement. • HGV access only needed in event of an unforeseen fault, or maintenance planned and agreed in the OEMP.	• To be used as a main access. • Right of access to farm buildings, as existing. • No requirement to serve agricultural use. • RoA for EA as existing
Sunnica West Site A: Site Access B on Chippenham Road	• 2.4m wide unmade track used by agricultural vehicles. • Provides access to several agricultural fields. • i) the right at all times to use all Access Roads within the Property ii) right of entry with or without machinery and equipment to woodland areas on the Property to thin and remove timber iii) right of entry to connect and draw water from hydrants	• To be used as a secondary access. • No requirement to serve agricultural use where PVs will be installed. • Two agricultural	• No requirement to serve agricultural use where PVs will be installed, so significant reduction in usage. • Two agricultural fields will require access, as existing. i) the right at all times to use all Access Roads within the Property ii) right of entry with or without machinery and equipment to woodland areas on the Property to thin and remove timber iii) right of entry to connect and draw water from hydrants	• To be used as a secondary access. • Right of access to farm land, as existing. • No requirement to serve agricultural use where PVs will be installed.

		fields will still require access, as existing.	• Limited maintenance requirement for PV array, comprising occasional small level of LGV movement. • HGV access only needed in event of an unforeseen fault, or maintenance planned and agreed in the OEMP.	• Two agricultural fields will require access.
Sunnica West Site A: Site Access C on Dane Hill Road	• Existing 5.5m gated access to farm. • Provides access to agricultural land (Dane Hill Farm).	• To be used as a secondary access. • Right of access to Dane Hill Farm, as existing, including use of internal access track.	• Right of access to Dane Hill Farm, using internal access track. • No requirement to serve agricultural use where PVs will be installed. • Limited maintenance requirement for PV array, comprising occasional small level of LGV movement. • HGV access only needed in event of an unforeseen fault, or maintenance planned and agreed in the OEMP.	• To be used as a secondary access. • Right of access to Dane Hill Farm, as existing, using internal access track. • No requirement to serve agricultural use.
		•	•	
Sunnica East Site B: Site Access A on Elms Road	• Single unmade field access utilised. • Appears to be infrequently used by agricultural vehicles.	• To be used as a secondary access. • No requirement to serve agricultural use where PVs/BESS will be installed.	• To be used as an emergency access only in operation. • No requirement to serve agricultural use where PVs/BESS will be installed.	• To be used as a secondary access. • No requirement to serve agricultural use.
Sunnica East Site B: Site Access B on Elms Road	• Gated 5.5m wide unmade field access currently used by agricultural vehicles. • Access required for reservoir (grid ref TL685707) - a right of way with or	• To be used as a secondary access.	• No requirement to serve agricultural use where PVs will be installed. • Access required for reservoir (grid ref TL685707) - a right of way with or without vehicles, plant,	• To be used as a secondary access. • No requirement to serve agricultural use

	without vehicles, plant, machinery and equipment in order to gain access to and egress from the Reservoir Shed and the Borehole Shed and the Water Tank	- No requirement to serve agricultural use where PVs will be installed. - Reservoir access as existing.	machinery and equipment in order to gain access to and egress from the Reservoir Shed and the Borehole Shed and the Water Tank - Limited maintenance requirement for PV array, comprising occasional small level of LGV movement. - HGV access only needed in event of an unforeseen fault, or maintenance planned and agreed in the OEMP.	where PVs will be installed. - Reservoir access as existing.
Sunnica East Site B: Site Access C on Elms Road	- Gated 5.5m wide access currently used by agricultural vehicles. - Right of way for landowner with or without vehicles, plant, machinery and equipment over the Permanent Access Roads (During Option and Lease Period) - Rights of access for National Grid gas main which is just beyond the site entry (grid ref TL686713)	- Main access to construction car park. - No requirement to serve agricultural use. - Rights of access for landowner and National Grid as existing	- Main access to operational car park. - No requirement to serve agricultural use. - Right of way for landowner with or without vehicles, plant, machinery and equipment over the Permanent Access Roads (During Option and Lease Period) - Rights of access for National Grid gas main which is just beyond the site entry (grid ref TL686713) - Limited maintenance requirement for PV array, comprising occasional small level of LGV movement. - HGV access only needed in event of an unforeseen fault, or maintenance planned and agreed in the OEMP.	- To be used as a main access. - No requirement to serve agricultural use. - Rights of access for landowner and National Grid as existing
Sunnica East Site B: Site Access D and H on Newmarket Road (located between Worlington and the Red Lodge Dumbbell Roundabouts)	- Site access D is a 3.5m wide gravel access used by agricultural vehicles. - Site access D provides access to several agricultural fields. - Site access H is not an existing access. - Property – i) the right at all times to use all Access Roads within the Property ii) right of entry with or without machinery and equipment to woodland areas on	- To be used as a secondary access. - Access may need to be retained for agricultural vehicles for land not being used by	- Access may need to be retained for agricultural vehicles for land not being used by Sunnica (Access D). This is lower than at present - Site Access D is expected to be used infrequently during the operational phase for maintenance purposes. - Limited maintenance requirement for PV array, comprising occasional small level of LGV movement.	- To be used as a secondary access. - Access may need to be retained for agricultural vehicles for land not being used by Sunnica (Access D).

	the Property to thin and remove timber iii) right of entry to connect and draw water from hydrants	Sunnica (Access D). This is lower than at present • Property access as at present	• HGV access only needed in event of an unforeseen fault, or maintenance planned and agreed in the OEMP. • Site Access H is not proposed to be retained during the operational phase. • Access may need to be retained for agricultural vehicles for land not being used by Sunnica (Access D). • Property – i) the right at all times to use all Access Roads within the Property ii) right of entry with or without machinery and equipment to woodland areas on the Property to thin and remove timber iii) right of entry to connect and draw water from hydrants	• Property access as at present
Sunnica East Site A: Site Access E on Ferry Lane (Freckenham Road USRN: 14601046)	• 4.5m wide gravel farm access road, including triangular ‘island. • Provides access to agricultural land and farm buildings. A right of way with or without vehicles, plant, machinery and equipment over the Existing Access Roads and Permanent Access Roads to gain access to and egress from the Retained Land (reservoirs and farm buildings) (grid ref TL666739)	• To be used as a secondary access. • Right of access to farm buildings, as existing. • No requirement to serve agricultural use.	• Right of access to farm buildings, as existing. A right of way with or without vehicles, plant, machinery and equipment over the Existing Access Roads and Permanent Access Roads to gain access to and egress from the Retained Land (reservoirs and farm buildings) (grid ref TL666739) • No requirement to serve agricultural use. • Expected to be used infrequently for maintenance purposes and for access to the substation. • Limited maintenance requirement for PV array, comprising occasional small level of LGV movement. • HGV access only needed in event of an unforeseen fault, or maintenance planned and agreed in the OEMP.	• To be used as a secondary access. • Right of access to farm buildings, as existing. • No requirement to serve agricultural use.

Sunnica East Site A: Site Access F on Beck Road	• 6m wide unmade access track used by agricultural vehicles, bounded by concrete slab.	• To be used as a secondary access. • No requirement to serve agricultural use.	• Expected to be used infrequently for maintenance purposes and for access to the substation. • Limited maintenance requirement for PV array, comprising occasional small level of LGV movement. • HGV access only needed in event of an unforeseen fault, or maintenance planned and agreed in the OEMP. • No requirement to serve agricultural use.	• To be used as a secondary access. • No requirement to serve agricultural use.
Sunnica East Site A: Site Access G on Beck Road	• Existing 15m wide asphalt road surface with access to farm land and properties.	• Secondary access not for HGVs. Expected to be used infrequently. • No requirement to serve agricultural use. • Access to property to be retained	• Secondary access not for HGVs. Expected to be used infrequently. • No requirement to serve agricultural use. • Access to property to be retained. A right of way with or without vehicles, plant, machinery and equipment over the Existing Access Road • Right of Access to i) PRoW ii) flow gauging station (grid ref TL662732) and iii) potentially for construction/laydown for heritage/ecological areas •	• Secondary access not for HGVs. Expected to be used infrequently. • No requirement to serve agricultural use. • Access to property to be retained
Sunnica East Site B: Site Access I on Newmarket Road (between A11 and Golf Links Road)	• Existing access is currently blocked	• To be used as a secondary access. • No requirement to serve agricultural use.	• Not proposed to be retained during the operational phase. • No requirement to serve agricultural use. • Landowner retained right to i) the right at all times to use all Access Roads within the Property ii) right of entry with or without machinery and equipment to woodland areas on the Property to thin and remove timber iii) right of entry to connect and draw water from hydrants	• To be used as a secondary access. • No requirement to serve agricultural use.

Sunnica East Site B: Site Access J on Golf Links Road	• 3.5m wide unmade field access used by agricultural vehicles. • i) the right at all times to use all Access Roads within the Property ii) right of entry with or without machinery and equipment to woodland areas on the Property to thin and remove timber iii) right of entry to connect and draw water from hydrant • Access rights for Cadent and Bay Farm Power Limited assumed to be maintained due to leases (grid ref TL702729)	• Access is not proposed to be used for Sunnica. • Existing access rights • No requirement to serve agricultural use.	• Limited maintenance requirement for PV array, comprising occasional small level of LGV movement. • No HGV access. • No requirement to serve agricultural use. • i) the right at all times to use all Access Roads within the Property ii) right of entry with or without machinery and equipment to woodland areas on the Property to thin and remove timber iii) right of entry to connect and draw water from hydrant • Access rights for Cadent and Bay Farm Power Limited assumed to be maintained due to leases (grid ref TL702729)	• Access is not proposed to be used for Sunnica. • Existing access rights • No requirement to serve agricultural use.
Sunnica East Site A: Site Access K on Beck Road	• This is an existing access for agricultural use. • A right of way with or without vehicles, plant, machinery and equipment over the Existing Access Roads and Permanent Access Roads to gain access to and egress from the Retained Land (reservoirs and farm building) (grid ref TL666739)	• AILs only access • No requirement to serve agricultural use. • Existing access to Retained Land	• This will be used as an emergency access. • No requirement to serve agricultural use. • A right of way with or without vehicles, plant, machinery and equipment over the Existing Access Roads and Permanent Access Roads to gain access to and egress from the Retained Land (reservoirs and farm building) (grid ref TL666739)	• AILs only access • No requirement to serve agricultural use. • Existing access to Retained Land
Grid Connection Site Access A	• Existing National Grid Substation access	• To be used during the construction phase related to works to connect and maintain the connection, of the project to	• To be used during the operation phase related to works to connect and maintain the connection, of the project to the existing National Grid Burwell Substation. • Potential for existing use of access to be continued. • No routine access required for Sunnica.	• Access to the Grid Connection Routes A and B is not required during decommissioning as the cable and infrastructure will remain in-situ.

		the existing National Grid Burwell Substation. - Potential for existing use of access to be continued.	- Access for Sunnica only required in event of a fault being identified, remotely, TTM to be reinstated if necessary.	- Potential for existing use of access to be continued.
Grid Connection Site Access B	- No existing access	- Option 2 of the Burwell National Grid Substation Extension is not required. - Access required for cable connection.	- No routine access required for Sunnica. - Access for Sunnica only required in event of a fault being identified, remotely, TTM to be reinstated if necessary.	- Access to the Grid Connection Routes A and B is not required during decommissioning as the cable and infrastructure will remain in-situ.
Grid Connection Site Access C	- Existing farm access	- To be used during the construction of the grid connection. A smaller vehicle (10m rigid) than a 16.5m articulated HGV has been identified to use this access. - Potential for existing use of	- Potential for existing use of access to be continued. - No routine access required for Sunnica. - Access for Sunnica only required in event of a fault being identified, remotely, TTM to be reinstated if necessary.	- Access to the Grid Connection Routes A and B is not required during decommissioning as the cable and infrastructure will remain in-situ. - Potential for existing use of access to be continued.

		access to be continued.		
Grid Connection Site Access D to T	- Existing access points - F – private access (north of river) regularly used for 2 properties and multiple agricultural interests - H – access used for Breach Farm Solar Farm and Farm Buildings - P – rights for telecommunications mast access	- To be used during the construction of the grid connection. - Potential for existing use of access to be continued.	- Potential for existing use of access to be continued. - No routine access required for Sunnica. - Access for Sunnica only required in event of a fault being identified, remotely, TTM to be reinstated if necessary.	- Access to the Grid Connection Routes A and B is not required during decommissioning as the cable and infrastructure will remain in-situ. - Potential for existing use of access to be continued.