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ATTACHMENT 6

REVIEW OF GAS EMISSIONS FROM LITHIUM-ION BATTERY THERMAL RUNAWAY FAILURE — CONSIDERING TOXIC AND FLAMMABLE COMPOUNDS.

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Review article

Review of gas emissions from lithium-ion battery thermal runaway failure — Considering toxic and flammable compounds

Peter J. Bugryniec [a], Erik G. Resendiz [a], Solomon M. Nwophoke [a], Simran Khanna [b], Charles James [c], Solomon F. Brown [a,*]

[a] Department of Chemical & Biological Engineering, University of Sheffield, Sheffield, S1 3JD, UK
[b] Department of Materials, Imperial College London, London, SW7 2AZ, UK
[c] School of Chemistry, University of St Andrews, St Andrews, KY16 9ST, UK

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ABSTRACT

Lithium-ion batteries (LIBs) present fire, explosion and toxicity hazards through the release of flammable and noxious gases during rare thermal runaway (TR) events. This off-gas is the subject of active research within academia, however, there has been no comprehensive review on the topic. Hence, this work analyses the available literature data to determine how battery parameters affect the variation in off-gas volume and composition, to determine the flammability and toxicity hazards of different battery chemistries. It is found on average that: (1) NMC LIBs generate larger specific off-gas volumes than other chemistries; (2) prismatic cells tend to generate larger specific off-gas volumes than offer cell forms; (3) generally a higher SOC leads to greater specific gas volume generation; (4) LFP batteries show greater toxicity than NMC; (5) LFP is more toxic at lower SOC, while NMC is more toxic at higher SOC (respective to themselves); and (6) LFP off-gas has a greater flammability hazard. Further, recommendations are presented so that significant improvements in research can be made to advance the understanding of LIB off-gas further. Finally, this work is a critical resource to the battery community to aid the risk assessment of LIB TR fire, explosion and toxicity hazards.

1. Introduction

As with traditional transportation fuels (i.e. hydrocarbons such as petrol and diesel), electrochemical energy sources like Li-ion batteries (LIBs) have inherent safety risks related to fire and toxicity [1–5]. The maturity of the internal combustion engine (ICE) means that the hazards of vehicle fires under different scenarios are well understood. However, with the accelerating uptake of LIB-powered electric vehicles (in the road, rail and marine sectors) there is a concern that there will be a growing knowledge gap between understanding the hazards of traditional and alternative fuel vehicles [6]. There have been several reviews of the growing literature on LIB safety, focusing on the mechanisms of cell thermal runaway (TR) and fire phenomenon [6,7]. However there are no reviews that specifically and comprehensively analyse LIB off-gas which is known to be flammable (containing hydrogen and hydrocarbons) leading to explosion and loss of life [8,9]. Further, for those involved in or near a TR event, toxic gas emissions (e.g. CO and HF) present an additional threat. However, the composition of the off-gas is complex and needs extensive consideration.

The risk of fire, explosion or vapour cloud ignition extends to stationary energy storage, EVs and marine applications, where incidents have occurred in reality [e.g. 9–11], showing that this is a real and present hazard. Adequate risk assessments are required to manage and mitigate this fire/explosion hazard and to aid emergency responders in understanding hazards they may walk into [12,13]. However, this can only be done with accurate and extensive knowledge of the off-gas volume and components (i.e. H_2, hydrocarbons, flammable solvent vapours, CO_2 dilution effect) to determine the explosion potential of the off-gas in a given scenario. This is also true for the toxicity of the off-gas, where determining the extent to which individuals are at risk of breaching *Immediate Danger to Life and Health* or exposure limits is essential. For example, in scenarios where individuals are exposed to off-gas in confined spaces, such as from the failure of personal transport stored in the home [14,15] or EV failure in a car garage [4,16]. As will be shown below, there is no extensive analysis of LIB off-gas considering the influence of battery variables, which is necessary for a thorough understanding of its hazards.

There has been some work to understand the overall off-gas behaviour. Baird et al. [17] compiled the gas emissions of ten papers

* Corresponding author.
E-mail address: s.f.brown@sheffield.ac.uk (S.F. Brown).

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Nomenclature

DEC	Diethyl carbonate
DMC	Dimethyl carbonate
EC	Ethylene carbonate
EMC	Ethyl methyl carbonate
EV	Electric vehicle (automotive)
HRR	Heat release rate
ICE	Internal combustion engine
IQR	Inter quartile range
LCO	Lithium cobalt oxide
LFL	Lower flammability limit
LFP	Lithium iron phosphate
LIB	Lithium ion (Li-ion) battery
LMO	Lithium manganese oxide
LTO	Lithium titanate
NCA	Lithium nickel cobalt aluminium oxide
NMC	Lithium nickel manganese cobalt oxide
PC	Propylene carbonate
SEI	Solid electrolyte interphase
SOC	State of charge
THC	Total hydrocarbons
TR	Thermal runaway

showing gas composition related to different cell chemistries and SOC, while Li et al. [18] compiled the gas emissions of 29 tests under an inert atmosphere. However, in both cases, no analysis is made relating chemistry, SOC, etc. to off-gas composition. Instead, flammability limit calculations and flame speed analysis were conducted. The most compressive review to date is by Rappsilber et al. [19] who analysed 76 papers focusing on peak heat rate, total heat, CO emission, total gas volume, and HF production. However, the overall volume and specific CO emissions trends are determined by grouping all the cell chemistry data for each SOC, while for HF only LFP cells are analysed.

This work aims to address the lack of a comprehensive review of LIB gas emissions during TR via collating and analysing data available in the literature. Within this aim the objectives are to understand how battery parameters affect the variation in off-gas volume and composition, and what battery can be considered least hazardous. Overall it provides a crucial resource that can be used in the risk assessment of LIB TR fire and explosion hazards.

The remainder of the introduction will outline the demand for LIBs, explain what a LIB is and describe the hazardous thermal runaway phenomenon. Section 2 will then review the literature on LIB off-gas composition and toxicity. In Section 3 the methods are presented for gathering and processing the literature data. Section 4 presents the analysis and discussion of the literature data. Section 5 provides concluding remarks.

1.1. Overview of lithium-ion batteries and thermal runaway

From powering personal electronics devices, LIBs are becoming the widely adopted energy source for automotive electric vehicles (EVs) and personal transport (bicycles and scooters). They are also increasingly used in ships and trains as auxiliary or primary power sources. Further, the aviation sector is also developing EVs based on LIB energy sources for electric vertical take-off and landing (eVTOL) as well as for light/short hall aircraft. Lastly, LIBs are also used in commercial battery energy storage (BESS) for grid support as well as domestic energy storage. With such growing use in terms of quantity and scale, there are increasing opportunities for LIB failure to cause greater harm. This is specifically true in certain situations where failure is more critical, such as in the marine and aviation sector where there is limited scope to distance people and assets from the failure.

LIBs are widely used as they have a high energy density, long cycle life and are low cost. Cell performance can be altered by materials selection, with common cell chemistries consisting of lithium cobalt oxide (LCO), lithium iron phosphate (LFP), lithium manganese oxide (LMO), lithium nickel cobalt aluminium oxide (NCA), lithium nickel manganese oxide (NMC) and lithium titanate (LTO). Generally NMC and NCA are used as high-energy cells, while LFP cells have a lower specific energy capacity but a larger specific power capacity and longer life span [20]. Further, battery performance (energy and power capabilities) is scalable by the number and configuration (series and parallel connections) of cells. Cells can be manufactured in different forms, commonly cylindrical, pouch or prismatic with capacities ranging from 1 Ah to 300 Ah. These characteristics allow LIBs to be customised for the variety of different applications mentioned above. However, even with these advantages, LIBs suffer from the phenomenon of thermal runaway (TR), explained in the next section.

1.1.1. LIB thermal runaway

The process of TR, see Fig. 1, involves the exothermic chemical decomposition of the battery cell materials leading to vast heat generation and temperature rise. This is accompanied by the generation of gasses from the decomposition process that can be flammable and toxic, and can lead to smoke, hot sparks and jet flames ejected from the cell [6]. Many reactions take place during the decomposition of the cell; however, the main stages consist of solid electrolyte interphase (SEI) breakdown, anode-electrolyte reaction, cathode-electrolyte reactions and electrolyte decomposition, see Table 1 for further details. Further, in a module or pack the heat from one cell can cause a cascading failure or propagation throughout the pack, increasing the overall hazard from failure. For module or pack failure this includes the production of large amounts of flammable gas that can lead to explosions [8,9].

Typically this occurs when the off-gas is confined to an enclosed space, thus not naturally dissipating like in the open, and either (1) an ignition source occurs when the fuel-air ratio is in the explosion range [8]; or (2) if additional air is allowed to enter (by opening a door to address the failure [9]) bringing the fuel-air ratio from above the upper explosion limit (UEL) into the explosion range. However, at least one unconfined off-gas explosion has taken place, where a large cloud of smoke accumulating around an electric bus suddenly erupts in flames [10], indicating that this smoke is a vapour cloud igniting [21]. This behaviour is complex, so to understand this hazard more it is important to determine how much volume and what species of gases are generated for different cell chemistries, forms, SOC, scale (cell/module/pack) and abuse.

2. Gas generation and toxicity — literature review

This section summarises the findings of individual literature sources regarding volume of gas produced (Section 2.1), gas composition (Section 2.2), toxicity (Section 2.3), presence of electrolyte vapour (Section 2.4), other influential factors including the effect of abuse scenarios (Section 2.5) and results from module and pack tests (Section 2.6).

2.1. Gas volume produced

The volume of gas LIBs generate during TR can be influenced by several conditions, including capacity, SOC and chemistry. At 100% SOC LFP cells are shown to generate a lower volume of gas than other chemistries (LCO, NMC, LMO), 0.4 L/Ah to 1.4 L/Ah versus 1.28 L/Ah to 21 L/Ah respectively [24–32]. In contrast, large NMC prismatic cells (41 Ah) and LFP cells (5.5 Ah) have been shown to generate similar off-gas volumes, 1.64 L/Ah and 1.83 L/Ah respectively (in nitrogen) [33]. While, LTO cells have been shown to generate significantly more off-gas than LFP cells, but less than NMC [34]. Further, higher nickel-content

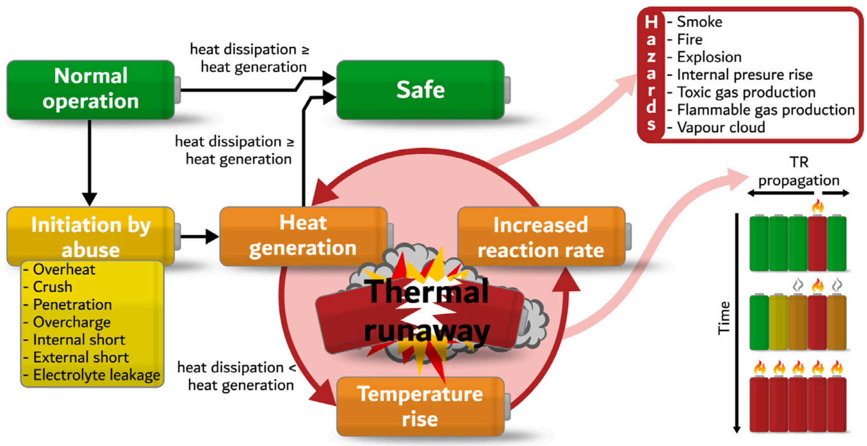


Fig. 1. Process of thermal runaway from initiation to propagation and resulting hazards [22].

Table 1
Summary of main reactions of LIB cell TR failure.
Source: Edited from [23].

Temperature (°C)	Reaction behaviour
>70	Li salt decomposition and reaction with solvent and Solid electrolyte interphase (SEI)
90–130	SEI breaks down leading to anode-electrolyte reaction. Low heat generation.
90–230	Li-electrolyte reaction occurs, leading to gas production e.g. C_2H_4, C_2H_6 and C_3H_6.
120–220	Electrolyte vaporises, leading to additional gas generation, cell pressurisation and initial venting. Separator melts at 130°C to 190°C.
160	Heat generation increases — from "self heating" to "thermal runaway". Violent gas and particle release (second venting).
200–300	Electrolyte decomposition occurs. At TR there is a rapid temperature rise, the metal oxide cathode decomposes to produce oxygen. O_2 leads to the oxidation of the electrolyte -> CO_2 and H_2O

NMC cells produce more gas than counterparts with less nickel [31,32]. Overall, the absolute vent gas volume increases with capacity [31, 32,35]. Limited work has compared cell forms, but NMC pouch and prismatic cells have been shown to generate similar volumes of gas production [36].

In many studies gas volume production is shown to increase as SOC increases for various chemistries, including NMC [23,30,37–39], LFP [25,40], NCA [25] and LCO [26]. However, little to no correlation between gas volume and SOC is observed in some studies on LFP and NMC cells [25,41]. Further, the greatest increase in emissions is typically seen over the range of 50% to 100% SOC [7,30]. Also, the increase in gas production with SOC has shown to be greater for NCA than for LFP cells. While at higher SOC LFP is typically shown to produce less off-gas than other chemistries, at lower SOC volumes can be comparable between chemistries, but in some cases LFP can generate more [7,25]. Increased gas generation at higher SOC is attributed to higher electrode potentials and more reactive cell materials [7]. The occurrence of combustion may also have an effect. When the failure of NMC cells did not lead to combustion (at 0% SOC) more gas production was recorded [41].

The peak rate of gas production has been shown to be proportional to SOC [7,39], while in other work this is not true [42]. Peak gas rates of individual species (CO, CO_2 and HF) have been shown to increase with SOC [43].

2.2. Gas composition

The main components of the off-gas are CO_2, CO, H_2 and hydrocarbons, while under certain conditions significant amounts of electrolytes and water can be present. The list of hydrocarbons generated can be many, but those typically measured/reported are CH_4, C_2H_6, C_2H_4, C_2H_2, C_3H_6 and C_3H_8. Further, there are possibly hundreds of components present in the off-gas, including non-hydrocarbons and toxins, that are infrequently reported [44–46]. The toxic components of main concern are CO, HF, HCl, HCN, NO_x, and SO_2 [7]. Table 2 summarises the hazards and exposure limits of the main off-gas components. Exposure limits are the concentrations of hazardous substances in air, averaged over 8 h or 15 min (long-term and short-term limits respectively), that are set to prevent harmful effects on people's health [47]. The reaction mechanisms towards species production are well discussed in the literature [see, for example, 24,25,32,37,48–51] and are not a topic for discussion here.

Comparing the off-gas composition from different sources highlights the variation in components and their volume fractions between and within chemistries. Typically, literature sources identify LFP as generating more CO_2 and H_2 than other chemistries that generate mostly CO and THC, in terms of volume fraction [24,32,34,56]. However, high levels of H_2, CO_2 and lower levels of CO have been reported in NMC cells [33], while higher CO_2 volumes have been reported for NCA compared to LFP cells [25]. It has been reported that the percentage of CO and H_2 production is proportional and inversely proportional to energy density, respectively [32]. This inherently links to nickel content for the NMC cells; however, later work shows less correlation [31]. Further, comparing solid-state cells versus "typical" Li-ion cells shows a reduction in gas production (by 10%) and a lower proportion of THC and H_2 (by 30% each), while the proportions of CO_2 and CO are larger (by 20% for CO) for the solid-state cells [57].

Koch et al. [27] have done one of the most extensive testing regimes of 51 NMC cells ranging from 20 Ah to 80 Ah. Significant amounts of

Table 2
Common LIB off-gas components, hazards and exposure limits.

Substance	Hazard[a]	Exposure Limit, 8 h (mg/m^3)[b]	Exposure Limit, 15 min (mg/m^3)[b]
Carbon dioxide, CO_2	Cause headaches, dizziness, confusion, loss of consciousness, and asphyxiation at high concentrations [52].	9150	27 400
Carbon monoxide, CO	Toxic if inhaled, may damage the unborn child, causes damage to organs through prolonged or repeated exposure and is an extremely flammable gas.	23	117
Hydrogen, H_2	Extremely flammable.	See note[d]	
Hydrocarbons	Flammable.	See note[d]	
Hydrogen fluoride, HF	Fatal if swallowed, is fatal in contact with skin, is fatal if inhaled and causes severe skin burns and eye damage.	1.5	2.5
Hydrogen chloride, HCl	Severe skin burns and eye damage, is toxic if inhaled, may damage fertility or the unborn child, causes serious eye damage, may cause damage to organs through prolonged or repeated exposure, may be corrosive to metals, may cause respiratory irritation and contains gas under pressure and may explode if heated.	2	8
Hydrogen cyanide, HCN	Fatal if swallowed, is fatal in contact with skin, is fatal if inhaled, causes damage to organs through prolonged or repeated exposure, is very toxic to aquatic life (with long lasting effects) and is an extremely flammable liquid and vapour.	1	5
Nitrogen dioxide, NO_2	Fatal if inhaled, causes severe skin burns and eye damage; and may cause or intensify fire (oxidiser).	0.96	1.91
Sulphur dioxide, SO_2	Severe skin burns and eye damage and is toxic if inhaled.	1.3	2.7
Solvents	Highly flammable liquid and vapour [53]. Very irritating to eyes, skin and airways [44].	DEC 700, PC 8.5[c]	DEC 1000, PC 8.5[c]

[a] Cited from the European Chemicals Agency [53], unless otherwise stated.
[b] Cited from the HSE [47], unless otherwise stated.
[c] Cited from the IFA [54] for the solvents DEC (Romania) and PC (Germany), other common electrolyte solvents (e.g. EC and DMC) are not listed.
[d] Hydrocarbons, such as CH_4, are described as acting as simple asphyxiants without other significant physiologic effects when they are present in high concentrations, hence are not given limit values as the significant factor is the availability of oxygen [55]. This is assumed for H_2 as well.

CO_2 are recorded at low-vent gas volumes as combustion could still be complete even in the limited oxygen availability of the closed system. Koch et al. found that (for vent gas volumes greater than 50 l where combustion was limited) 7 components make up over 99% of the off-gas volume. These components (and their average volume proportions) are CO_2 (36.6%), CO (28.3%), H_2 (22.3%), C_2H_4 (5.6%), CH_4 (5.2%), C_2H_6 (1.0%) and C_3H_6 (0.5%). These averages have a large variation, with CO, CO_2 and H_2 being within the error of each other. Further, there is no correlation between composition and the vent gas volume.

SOC is shown to affect the off-gas composition ratio and the number of components produced. At 0% SOC the gas can be mainly CO_2 [17], or a few components (~5) including CO and solvents, while this can reach several tens of components at higher SOC [58]. Generally, it has been found that the percentage volume of CO_2 in the off-gas reduces while CO increases as SOC increases for various chemistries (LCO, NCA, LFP) [7,17,25,26,59]. At the same time, THC and H_2 have been found to remain steady across SOC for LCO cells [26]. For LFP and NCA cells H_2 is seen to increase in volume fraction [25], while H_2 and THC are found to increase in volume fraction for LCO and LFP cells [17], with SOC. However, other works have shown contradictory results, where CO_2 increases and THC reduces with SOC increase [37], or the fraction of THC reduces along with CO_2 with SOC increase [59]. Also, H_2 was only detected at 100% for LFP cells [42].

Peak concentrations of gases and production rates increase with SOC [39,60,61]. However, the reduction of CO_2 volume fraction can be attributed to the increase in absolute production of other gases while CO_2 concentration remains stable [60,62]. The reduction of hydrocarbons and increase in CO and CO_2 at higher SOC (in a nitrogen atmosphere) has been attributed to combustion events [37,39], however Willstrand et al. [7] shows contradictory behaviour. Nevertheless, it has been noted that higher SOC enhances combustion, leading to a greater HRR and higher concentrations of CO_2 and CO [63,64]. More so, the relationship of combustion efficiency (turning CO to CO_2) is complex and dependent on temperature (generally proportional to SOC), abuse method, oxygen availability and gas generation rate [7].

Studying the flammability limit of cell off-gas, for NMC cells (18650, 3.5 Ah) the lower explosion limit (LEL) increases up to a maximum of 10.15% at a SOC of 50% and then reduces at higher SOC, while the upper explosion limit (UEL) continually increases [65]. This means a SOC of 50% has the lowest risk of combustion in an open space. However, the narrowest flammability range is at a SOC of 30%, hence this SOC is recommended for the storage and transport of LIBs. The trend in LEL is attributed to the change in multi-carbon chain gas components. When there are more gas components with longer carbon-chains the LEL reduces.

Electrolyte composition is shown to affect the off-gas from cell abuse. For different LFP 18650 cells, where EMC is always present and makes up approximately 50% of the electrolyte solvent, there is a weak trend between increased EMC proportion and reduced gas generation, while the percentage of CO_2 increases with increased EMC proportion [66]. Studies on electrolytes alone have shown that the concentration of lithium salt affects the ratio of off-gas species, while an increase in salt concentration leads to greater instability and gas production [67]. The individual solvents (e.g. EC, DEC, EMC and DMC) also vary in stability and gas volume production, with EC and DEC being the least thermally stable and reactivity increasing with the addition of $LiPF_6$ salts [68]. Further, the use of binary mixtures leads to electrolytes that have stability broadly related to the solvent-mole ratios. For EC, EMC and DMC solvents with 1.2M $LiPF_6$ gas emissions are dominated by CO_2 (70%), but for DEC (1.2M $LiPF_6$) CO_2 and C_2H_6

account for 30% each; however, tens of components are recorded in total in all cases. Similar behaviour has been shown by Fernandes et al. [69], but with thermal decomposition of EMC and particularly DMC occurring at lower temperatures. Further, there is uncertainty in the actual reaction mechanism for the thermal decomposition of battery solvents [70].

Additionally, the presence of the cathode and anode materials in a cell complicates the reaction behaviour. Intercalated lithium in the anode can react with the solvents to produce hydrocarbons, while oxygen released from the cathode decomposition can lead to decomposition [71,72]. The reaction pathways to gas generation are numerous and complex and the readers are referred to existing reviews on the mechanism of thermal runaway, see Refs. [71,72]. Additives have also been used to improve anode-electrolyte stability and impede fires [73]. Flame retardants can reduce fires leading to less CO_2 but more H_2 and CO. Further, in the near future it is expected that all-solid-state cells will be commercial, in which their solid electrolyte has increased stability and reduced heat of reaction, dramatically improving cell safety but with little know of the amount and type of gas produced [74]. Due to these numerous variables (i.e. solvents, solvent ratios, salt concentrations and additives) and that few works know or record the electrolyte composition in battery safety/off-gas tests, electrolyte composition is not considered in further discussions as a variable affecting off-gas characteristics.

2.3. Toxicity

Several toxic compounds commonly discussed include CO, HCl, HCN, NO, SO_2, HF, fluorinated carbonates, POF_3, COF_2, acrolein, and formaldehyde [29,38,50,60,61,75–77]. Non-quantified work has detected up to 35 toxic substances which vary with chemistry and SOC [78]. Understanding the presence of these compounds is important as inhalation of these gasses can result in dizziness, headache, loss of consciousness, coma or even death [6].

The risks of these emissions, however, depend on the scenario of the incident. In the outside environment, HF will likely rise and quickly dissipate. Whereas, in enclosed spaces HF will increase and be problematic if gasses are not evacuated. More full-scale tests are needed to fully establish this and assess the effects of fire suppression on toxicity.

For LMO cells the total amount of HCl generated remains stable with SOC but the amount of SO_2 increases with SOC, while NO shows no correlation [60]. The change in HCN concentration is also shown to be minimal over increased SOC [38]. For NMC prismatic cells (94 Ah), more SO_2 was produced at 50% SOC than at 100% SOC while the maximum temperature was 510°C compared to 620°C, respectively [77]. The rate of HF production increases with SOC [61,75,76], while for a stack of LFP pouch cells the peak HF production rate is seen at 50% SOC [79].

For LCO, NCA and LFP cells, it is shown that there is a downward trend of specific HF production with SOC increase [50,60,61,75]. In some cases for LFP cells, HF is only detected at low SOC (at or below 25% SOC) [7]. However, peak HF production for LFP cells has been seen at 50% SOC [79] or 100% SOC [80]. Also, CO and HF production has been shown to increase with SOC (for 22 Ah LFP cells) [42].

Comparing HF production between cell chemistries, LCO prismatic and LFP cylindrical cells are shown to produce similar specific amounts of HF, so do NCA and LFP pouch cells [76], as well as LFP and LMO/NMC [29]. However, Sturk et al. [75] show that LFP cells generate significantly more HF than their NMC counterparts. HF is found to be the largest contributor to toxicity for LFP cells, while for LCO and NMC it is Acrolein [50]. From this, LFP cells produce the largest theoretical contamination volume (300 m^3) versus LCO and NMC cells (200 m^3) (considering 18650 cells). Overall, there is no strong trend for the theoretical contamination value with SOC, because as HF decreases with SOC there is an increase in other toxins such as CF_4.

For other toxins, the number of combustion organic products increases with SOC, up to a SOC of 100%, and then there is a significant reduction at a SOC of 150% [81]. In total, over a hundred species were detected, but more products are seen in LCO, NMC and LMO cells than in LFP cells. For NMC and LCO cells a higher SOC showed more substances, while for LFP cells the greatest amount of substances was detected at 30% SOC [78]. Six very toxic substances identified as 2-propenal, methyl vinyl ketone, propanedinitrile, propanenitrile, 1,2-dimethyl-hydrazine and thiocyanic acid ethyl ester could be detected. Further, phosphonofluridates have been detected in NMC but not LFP cells [44].

The cell form may influence HF production. LFP pouch cells are shown to produce an order of magnitude more HF than cylindrical cells [60,76]. However, NMC pouch and prismatic cells show similar volumes and composition of gas, including HF [36]. Further, abuse type can affect toxic gas generation. Thermal abuse produces a greater contamination volume than nail penetration, as penetration overall produces less gas [50].

While the dependence of SO_2 generation on SOC is not definitive, one theory attributes it to the fact that the formation of SO_2 requires significant heat [60]; hence, it only occurs at higher SOC where the TR temperature is higher. Conversely, less HF is theoretically formed at higher SOC as the higher TR temperatures promote bond breaking leading to the production of smaller molecules [50], or give rise to more complete burning [82] where the reaction between HF and hydrocarbons can consume the free HF [83], aided by the increase of hydrocarbons at higher SOC. The increase of CF_4 with SOC is not explained [50]. The fluorine within the cell materials can also lead to POF_3, from reaction with water, which may be more toxic than HF [6]. Even though HF has a high toxicity rating, the large amounts of CO make this the main toxicity concern [84].

2.4. Electrolyte vapour

During TR, the electrolyte can exist in the off-gas as a vapour and presents additional flammability, irritability and toxicity hazards. The combined off-gas/electrolyte mixture is sometimes termed the "vapour cloud" [21] and can exist due to a lack of heat initiating combustion or due to a lack of oxygen limiting oxidation such that the solvent remains as a fume [45].

The solvents DMC, EMC and DEC (common in electrolytes) are highly volatile with low boiling points of 90°C to 129°C and high relative evaporation rates (between 1 and 3) [85]. PC and EC can be considered less volatile with higher boiling points of 242°C to 249°C and lower relative evaporation rates (<0.005). The vapour densities of solvents used in Li-ion cells are heavier than air and so will accumulate at the ground when the liquid solvent evaporates. However, the relative vapour density (ρ_{rel}) for a chemical compared to air (where $\rho_{rel} = 1$, $\rho_{rel} < 1$ and $\rho_{rel} > 1$ would correspond to a vapour that is neutral, buoyant and dense respectively) depends on the molecular weight of the vapour, temperature of the vapour, temperature of the air and the saturated concentration of the vapour in the air [86]. Therefore, the behaviour of a TR event, i.e. the temperature of failure (influencing vapour temperature), the rate and magnitude of vapour discharge and the rate of vapour dispersion, will influence how the relative vapour density changes with time. Further, the presence of solvents still in the liquid state, as aerosols, can lead to a cloud initially behaving as dense due to the relatively heavy droplets even if the emitted vapour mixed with air would normally (initially) be buoyant or dense [86]. As such, initially buoyant clouds can turn dense and vice-versa, adding further complexity to understanding and predicting the hazard of vapour cloud explosions in relation to LIBs.

For the common electrolyte carbonates, the volume of solvent required to evaporate to reach hazardous levels with mild transient effects (within a 1-meter distance from a vehicle) is 2.24 mL, 1.40 mL, 0.17 mL, 0.13 mL for DMC, EC, PC and DEC respectively. Lithium salts lead to HF production, which is toxic and corrosive: 20 mL of 1 M $LiPF_6$ electrolyte can release enough HF in a 62 m^2 room to cause serious permanent health effects. Further, Diaz et al. [50] have shown that a single 18650 cell can lead to a contaminated volume of 100 m^3 to 400 m^3 based on the off-gas considering emitted solvents, CO, HF and other toxic components.

Although the presence and hazards of the electrolyte vapour are known, it is not frequently measured in gas analysis studies. However, overcharging of LFP cells shows that the off-gas can have a composition that is 60% electrolyte (where no fire or burning is noted in this test) [48]. Other work has detected, but not quantified, the existence of the solvents [7,29,87]. For various cell chemistries, the most abundant compounds were stated to be carbonates, which for LFP cells were DEC and EMC, and for NMC cells where DMC and EMC [44].

2.5. Composition in relation to other factors

The composition of off-gas is shown to vary with different stages of TR. At initial venting, CO_2 dominates, followed by hydrocarbons and a minimal amount of H_2 [88,89]. In some cases, electrolyte solvents are recorded and in a significant quantity, while in others, H_2 is not present [23,37,48]. During TR there is a marginal increase in H_2, while during the deflagration there are significant amounts of CO and H_2 [88]. Also, electrolyte solvents are not recorded after TR [23]. However, aged cells show more CO and hydrocarbons at venting compared to fresh cells [89].

Other phenomena exist, including the retentively cool off-gas released early on in TR (compared to later stages) sinking to the floor (due to the vapour densities of solvents) [41]. Comparing “standard” versus “violent” TR, where violent is defined as maximum cell temperature over 250°C and more than 0.5 l of off-gas, there is more CO_2 and H_2 in violent cases [90]. LFP cells show no visible outburst of gas at SOC lower than 50% [82]. Similarly, for large LFP cells no fire or TR is seen at 0% SOC, but at 50% and above sustained jet fires are present [42].

The volume of gas produced by different abuse methods has been compared. Abuse by puncture (from projectile) shows less gas production than other failure modes (wedge-shaped penetration, impact and thermal) [2]. Different thermal abuse methods are shown to lead to similar results, except for reactor heating (where decomposition of electrolyte solvent occurs on the hot reactor walls after venting) leading to more gas being produced [28]. However, other work shows that a greater heating rate increases gas generation volume [90]. It is suggested that more gas is produced in air (allowing for combustion) than in a nitrogen atmosphere because the pyrolysis of organics produces a solid char [50]. Overcharge is shown to generate more gas (by more than 50%) than over-temperature or nail penetration [36]. Aged cells, with less remaining capacity, show less gas generation as more electrolyte is consumed in cells with less remaining capacity [91]. On overcharge, more gas is generated as a cell is increasingly overcharged [92], with the amount of CO_2 increasing at a greater rate than other gases (CO, H_2 and THC) [66,92,93]. However, Willstrand et al. [7] did not show any evidence to suggest that the abuse method affects the total gas volume produced or composition; but the abuse type does affect gas production rate, mass loss, and maximum temperature of the cell as much as its state of charge.

In open space, less gas is produced at a lower rate with the exception of CO_2 which has a higher rate [39]. Suggesting that more complete combustion occurs in open space, which conversely implies cells in a pack may not undergo complete combustion. In a nitrogen atmosphere hydrocarbons form a greater percentage of the off-gas than when abused in air [37]. For short circuit tests, more gas is produced in a nitrogen atmosphere and mainly consists of H_2, CO_2, CO and CH_4, while in air the off-gas is mostly CO_2 and CO [94]. However, repeats of the same test can result in significant differences in results [95].

2.6. Abuse at larger scales

Studying the TR of LIBs at different scales, i.e. from cell to module and pack level, is important to understand how the hazards scale with battery size. However, only a few academic studies focus on the pack (i.e. EV) level concentrating on fire and toxicity behaviour.

EV fire safety has focused on similar gases to research on a cell level, namely CO_2, CO, THC, NO_x, HF, HCl, HCN and heavy metals. The overall gas composition is similar between ICE and EVs. Over 95% of the combustion gas is CO_2, a few percent is CO and less than 0.5% is THC, HCl, HF, NO_x and SO_x individually [1,3,4]. The most significant difference in EV and ICE vehicle toxicity is the quantity of HF. Lecocoq et al. [3] and Truchot et al. [1] both show that EVs generate double the amount of HF than ICE vehicles (1.5 kg versus 0.7 kg), while Willstrand et al. [4] show that EVs generate an order of magnitude greater HF than ICE vehicles (0.7 kg versus 0.01 kg). Further, the peak HF generation rate (3 g/s to 4 g/s) is similar in both EV and ICE vehicles, attributed to the rupture of the air-conditioning refrigerant [1,3]. However, the HF generation rate is greater for EVs than ICE vehicles (1 g/s versus 0 g/s to 0.5 g/s) at times later on in the vehicles burning — presumably due to the battery burning. HCl percentage composition is similar between vehicle types. In addition to gas production, battery fires lead to heavy metal deposits [2] that results in more heavy metals being produced in greater quantities by EV fires [5]. Due to the low toxic thresholds of these toxic substances, it is important to consider them for toxic evaluation, even though the total amounts produced are low [1].

Further to this discussion, it should be stated that these EV studies consider abuse leading to TR leading to fire, and not any situation where there is TR without fire. However, it is noted that there have been instances in the public where EVs have gone into TR without fire until the ignition of the off-gas [96]. Hence, there is a need to understand why and how large-scale battery TR failure leads straight to fires in some instances and to gas emissions and explosion hazards in others.

Moving up the battery scale (from cell to stack to module) an increasing volume fraction of CO, CO_2, and H_2O is observed [8]. Further, the release of HF increases as module size increases, presumably due to simultaneous cell burning [75]. The production of gas (specific to capacity) is greater for a group of 10 cells with a similar capacity to one large cell, the gas production is 25% more at 100% SOC [97]. However, at 75% and 50% SOC there is a negligible difference between the group of cells and a single large cell. An array of the same capacity of a cell shows a tendency for higher CO_2 and CO fraction, with less H_2. Further, in general, the greater number of cells and cell capacity leads to greater EV fire risk [6]. However, it is shown heat release rate (HRR) does not scale linearly with capacity, because not all cells burn at once. Hence, one should take caution scaling other hazards relating to batteries linearly with capacity.

2.7. Summary

In general, cell capacity and energy density are influencing factors of TR behaviour, affecting emitted venting gas volume, self-heating onset temperature and cell mass loss [27]. On a cell level, gas production typically ranges from 1 l/Ah to 3 l/Ah given all chemistries and in absolute terms increases with cell capacity. Under direct comparisons, LFP cells produce less gas than other chemistries in most studies. However, separate studies show that LFP may produce gas (l/Ah) on a similar scale to high-energy cells. Further, many studies have shown that gas production increases with SOC, but this is not true in all studies nor for all chemistries.

The off-gas mainly consists of CO_2, CO, H_2 and hydrocarbons. However, the composition from the same as well as different cell chemistries and SOC varies considerably. The availability of oxygen (i.e. air vs inert atmosphere, or open vs closed space) affects the composition. Electrolytes can make up most of the off-gas but they are rarely recorded. Given an abuse scenario, the composition is also different depending on how violent and hot the TR event occurs. Limited data on the overcharge of NMC cells shows more CO_2 is generated at higher SOC, while for LFP electrolyte vapours are the main component. The composition of the off-gas changes throughout TR, early on at low temperatures the initial venting can be mainly CO_2, solvents or CH_4 (dependent on chemistry). This implies the hazard assessment should consider the different stages in TR and their relevance to fire/explosion risk. Many toxic components have been identified but HF and CO are the most recorded. It is shown a single 18650 cell can lead to a contaminated volume of 400 m^3 and toxicity remains an issue at all SOC.

No standard testing procedure is used within the academic literature, unlike, for example, the use of accelerated rate calorimetry to determine thermal hazards of cells. Many authors use custom equipment with different gas monitoring setups, open/closed systems and systems of different enclosure sizes. This increases the difficulty in comparing results from different research groups and should be a consideration of the community to resolve.

The above raises the following questions which we aim to answer in our analysis. How does the chemistry, form, capacity and SOC impact the:

- specific gas production?
- toxicity (specifically CO and HF production)?
- gas composition?

3. Methods

To allow for a definitive analysis of the off-gas behaviour from LIB TR, a comprehensive literature search of the topic needs to be ensured. To do so, the literature search was conducted with the keywords “lithium-ion” or “Li-ion” or “LIB” and “cell” or “battery” or “EV” and “abuse” or “thermal runaway” or “fire” and “off-gas” or “venting” or “gas analysis”. From this, 60 papers [1–5,7,8,23–43,46,48–50,56,58–61,75–77,80,82,88–95,97–104] were deemed as appropriate and used to collate data on scale of battery (from cell to EV), form of cell, chemistry of cell, elemental ratio of cell chemistry, abuse type, cell capacity, test capacity or energy rating, SOC, nominal voltage (of cell), gas testing equipment, rate of CO_2/CO/HF, duration of test, total volume or mass of off-gas and quantities of individual components (g, mmol or litres) or percentage ratios. Conversion between units (g, mmol or litres) was done assuming standard temperature and pressure. The compiled data is supplied in full in the Supplementary Data. The literature data is then used to understand the influence of cell chemistry, cell type, battery scale, SOC and atmosphere on off-gas characteristics. The method of gas analysis and abuse type are recorded but not analysed for effect on LIB off-gas, and neither is the equipment setup (particularly closed versus open), but comments are made in the discussions.

4. Results and discussion — analysis of Li-ion off-gas emissions from literature

4.1. Bibliography summary

Given the literature collated, it can be seen from Fig. 2 that over the past ten years there has generally been an increasing number of papers published each year investigating the LIB off-gas, which to date leads to a total of 60 papers used in this analysis. Further subdivision of the number of papers that study specific form, cell type and chemistry can be found in the supplementary material. Within these papers most (53) focus on cell level studies while only 12 investigate larger scales including only 2 studying EV packs, see Fig. S1(a). Note that the number of papers to study specific categories can sum to more than the total (60) papers analysed as some papers may study more than one category, i.e. multiple cell forms or chemistries.

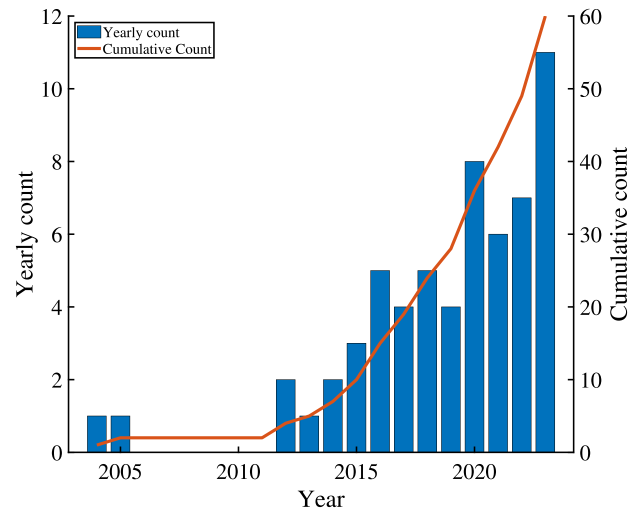


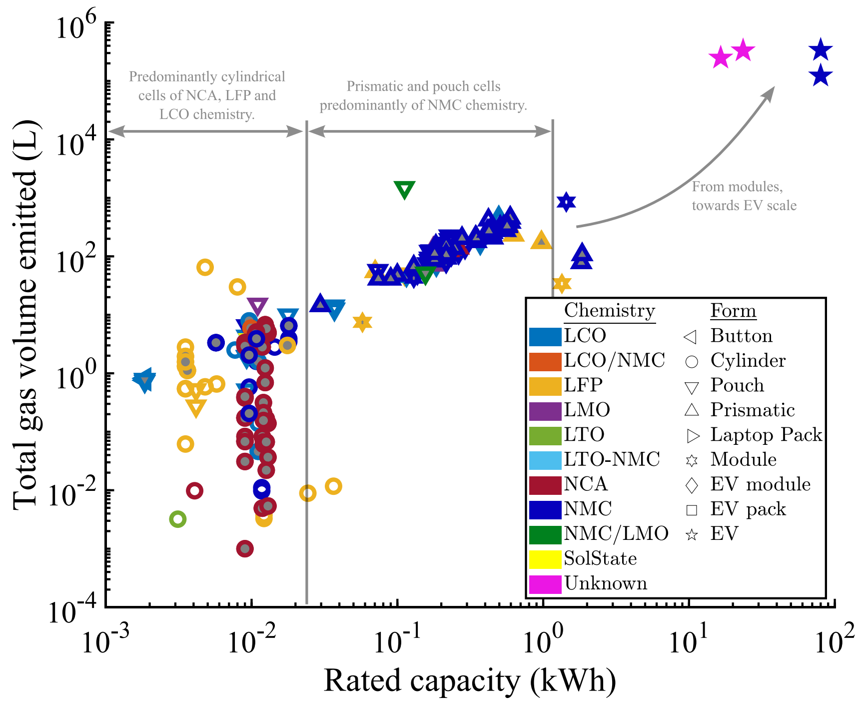
Fig. 2. Bibliography summary on a yearly basis, number of publications studying LIB TR off-gas.

At the cell level there are an approximately equal number of papers studying the off-gas of cylindrical, pouch and prismatic cells, see Fig. S1(b). Regarding chemistry, 31, 20 and 13 papers investigate NMC, LFP and LCO respectively, see Fig. S1(c). Further, NMC has mostly been studied in the past 4 years (2020–2023) with less studies on LFP in the last 3 years (2021–2023) than the 2 prior (2019–2020). Within the NMC chemistry a significant number of studies (over the entire date range) do not report the elemental ratios of nickel, manganese and cobalt, see Fig. S1(c). However, since 2020 there has been an increase in the number of studies reporting the elemental ratios, with the majority now being reported. In the last 2 years the most studied have been NMC811 and NMC622.

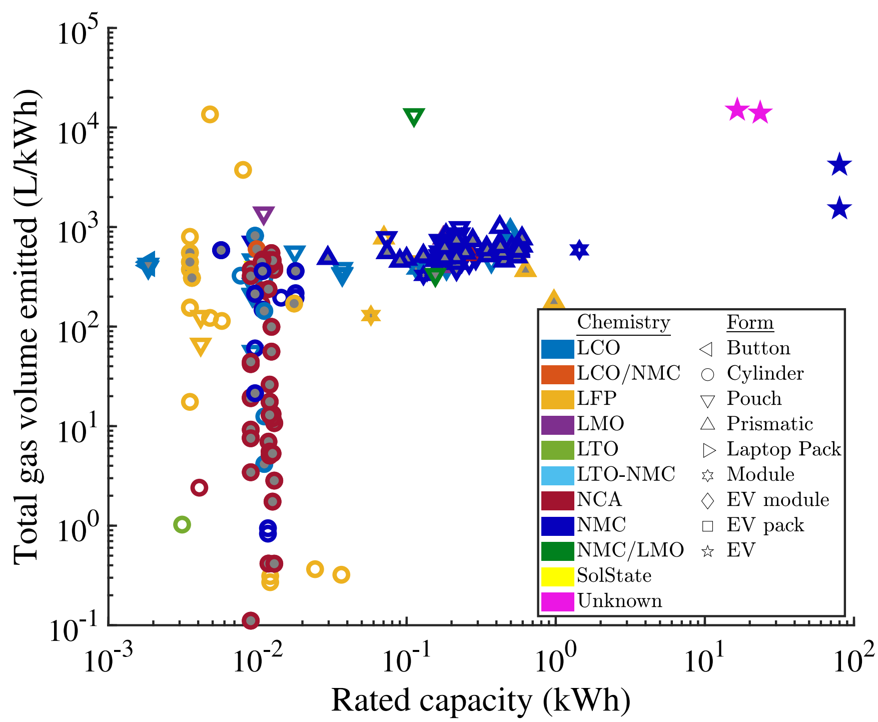
4.2. Total gas volume emitted

The first step in quantifying the hazard of LIB TR off-gas is determining the volume emitted. Fig. 3 presents the total amount of off-gas emitted at 100% SOC across a range of battery capacity scales, from cell to EV. This shows that as battery capacity increases so does the total amount of off-gas production. Further, it can be seen that below 0.02 kW h the results are mainly comprised of cylindrical cells with NCA, LFP and LCO chemistries. Above this, up to 1 kW h, the results are of prismatic and pouch cells, predominantly of NMC chemistry. For a more detailed view of these regions see Fig. S2 in the supplementary material. This highlights the lack of analysis of high capacity (10 Ah to 100 Ah) LFP pouch/prismatic cells. Interestingly, the results below 0.02 kW h show more variation than above this value. This suggests that cylindrical cells may have a larger range of off-gas production than pouch or prismatic cells.

Further to the absolute volume of off-gas, Fig. 3(b) presents the specific volume of off-gas relative to the LIB capacity. This reveals that there is no correlation between capacity and the specific off-gas volume. To assess this further, and to determine the relative variability of each cell type, Fig. 4 presents a box plot of the specific off-gas generation for each cell type. For all box plots in this work the shaded box is the inter quartile range (IQR), the horizontal line within the shaded box is the median and the whiskers are the minimum and maximum values (excluding outliers). Individual data points are displayed as red scatter points while points more than 1.5IQR from the shaded box are deemed as outliers. From this it can be seen that more gas is typically produced by prismatic cells (where median values are 598 L/kWh - air, 573 L/kWh - inert) and pouch cells (502 L/kWh - air, 408 L/kWh - inert) than cylindrical cells (156 L/kWh - air, 157 L/kWh - inert). This



(a)



(b)

Fig. 3. Total amount of gas emitted from LIB failure given rated battery capacity for batteries at 100% SOC considering all chemistries and form factors (a) absolute values, (b) specific values. Unfilled points are from tests conducted in air, grey filled points are from tests conducted in an inert atmosphere, coloured filled points are of an unknown SOC but assume 100% SOC for this plot.

is similar to the behaviour shown by Rappsilber et al. [19]; however, here there are 93, 56 and 72 data points used within the cylindrical, pouch and prismatic cells types, respectively, compared to 12, 5 and 3 in Ref. [19]. Furthermore, here the data is split by atmosphere — air or inert. For cylindrical and prismatic cells the medians are similar for each atmosphere, while for pouch cells the inert atmosphere leads to less off-gas production. The variation in off-gas production is similar for each cell type in air, while in an inert atmosphere pouch and prismatic cells have less variation than cylindrical.

Although Fig. 4 shows prismatic and pouch cells to produce more off-gas than cylindrical cells, Fig. 3 shows that for the collated data these cell types are predominantly NMC. For clarity, Table S1 shows the number of data points of each chemistry for each cell type in Fig. 4. From this it can be seen that the prismatic, pouch and cylindrical

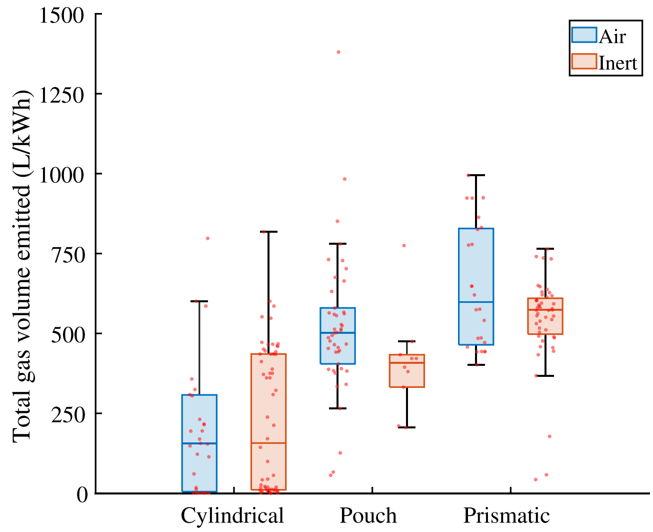


Fig. 4. Considering cell results only, the total amount of off-gas emitted from LIB failure at 100% SOC grouped by cell type. (The number of values in each category are *Form [Air, Inert]*: Cylindrical [31, 62], Pouch [46,10] and Prismatic [24, 48].).

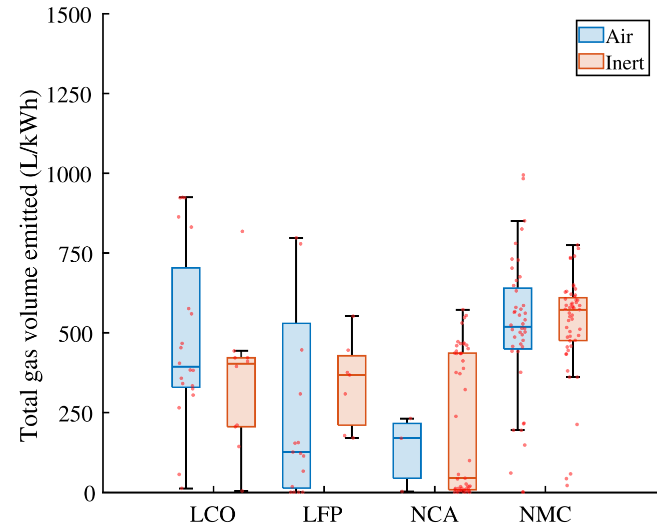


Fig. 6. Considering cell results only, the total amount of off-gas emitted from LIB failure at 100% SOC grouped by cell chemistry. (The number of values in each category are *Form [Air, Inert]*: LCO [20, 10], LFP [17, 7], NCA [3, 51] and NMC [44, 52].).

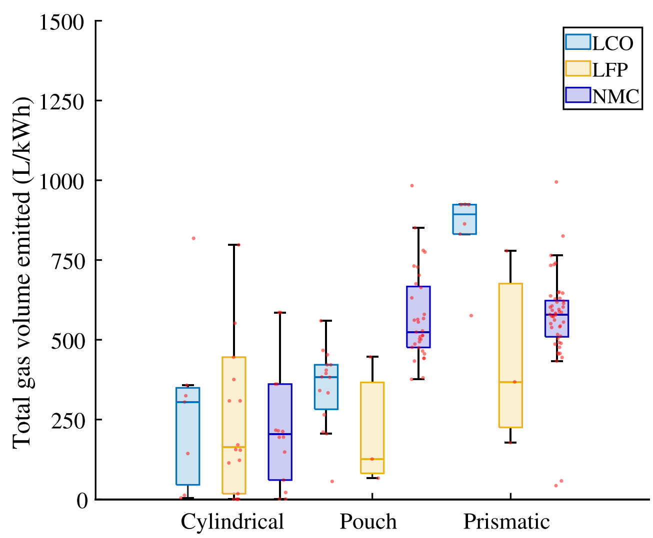


Fig. 5. Considering cell results for LCO, LFP and NMC chemistries, the total amount of off-gas emitted from LIB failure at 100% SOC grouped by cell type (both in air and an inert atmosphere). (The number of values in each category are *Form [LCO, LFP, NMC]*: Cylindrical [7, 18, 14], Pouch [15, 3, 33] and Prismatic [6, 3, 41].).

group data points are 68%, 59% and 15% NMC chemistry. As the literature has suggested (see Section 2.1), NMC produces more off-gas than other chemistries. Hence, it is necessary to analyse the off-gas volume regarding cell type and chemistry to determine if prismatic cells produce more off-gas due to their form or due to the data being mostly NMC. This is presented in Fig. 5 for LCO, LFP and NMC chemistries as the other chemistries lack data to compare across all cell types (see Table S1). Note that Fig. S3 shows outlines not present in Fig. 5 due to the scale used to improve clarity.

Fig. 5 shows that LCO prismatic and pouch cells have a greater generation of off-gas than cylindrical cells (where median values are 893 L/kWh, 383 L/kWh, 303 L/kWh - prismatic, pouch, cylindrical respectively). This is similar for the NMC chemistry, however pouch and prismatic cells produce similar amounts of off-gas (579 L/kWh, 524 L/kWh, 203 L/kWh - prismatic, pouch, cylindrical respectively). For the LFP chemistry, the increase in off-gas generation of prismatic cells relative to cylindrical (368 L/kWh - prismatic, 163 L/kWh - cylindrical) is less than the LCO and NMC chemistries. Also LFP pouch cells produce an off-gas volume (126 L/kWh) similar to cylindrical cells. Overall, from Figs. 5 and 6, it is likely that more off-gas is generated by prismatic, than pouch and finally cylindrical cells.

To corroborate the literature statement that NMC produces more off-gas than other chemistries (see Section 2.1), Fig. 6 presents the specific volume of off-gas production for LCO, LFP, NCA and NMC chemistries. Note that Fig. S4 shows outliers not present in Fig. 6 due to the scale used to improve clarity. Other chemistries have been recorded, see the compiled CSV data table in the supplementary materials, but are not presented due to lack of sufficient data. Fig. 6 shows, from the median of the data, that the NMC chemistry does produce more off-gas than other chemistries (LCO: 394 L/kWh, 403 L/kWh; LFP 126 L/kWh, 368 L/kWh; NCA 169 L/kWh, 44 L/kWh; NMC 519 L/kWh, 573 L/kWh - air and inert respectively). In an inert atmosphere it is likely that NMC cells produce more gas than other chemistries. However, in air there is a chance that NMC cells will produce the same amount of off-gas as LCO and LFP. Comparison to NCA chemistry in air is omitted due to the being only 3 data points for this set. Furthermore, given the available data, there is no definitive difference in gas volume production between the two atmospheres.

While Fig. 6 presents data at 100% SOC, Fig. 7 presents the off-gas volume for LCO, LFP and NMC chemistries over various SOC. This data is mostly of cells as only 2 data point in the 100% SOC group are for any other battery scale. Fig. S5 presents similar results for the additional chemistries LMO and NCA, but is not included in the main analysis due to the lack of data at lower SOC. From Fig. 7 it can be seen that there is a strong tendency for increased gas production at higher SOC for LCO and NMC chemistries, while for LFP the increase is less steep. Also, both LFP and LCO show that there is a possibility for more gas to be produced at 0% SOC than at 25% SOC. The median values of off-gas production are similar between LCO and NMC chemistries across SOC. While for LFP the median values are similar to LCO and NMC at SOC 25% and lower, but at higher SOC the LFP chemistry has a lower median. However, the LFP chemistry shows a large variation in off-gas volume at each SOC. As such, it is possible for them to produce as much off-gas as LCO and NMC at all SOC. Further, due to the variation in the NMC chemistry it is possible that they themselves could produce similar or more off-gas at lower SOC than at higher SOC. It should be noted that there are significantly less data points at SOC less than 100%, hence this should be a focus of the academic community.

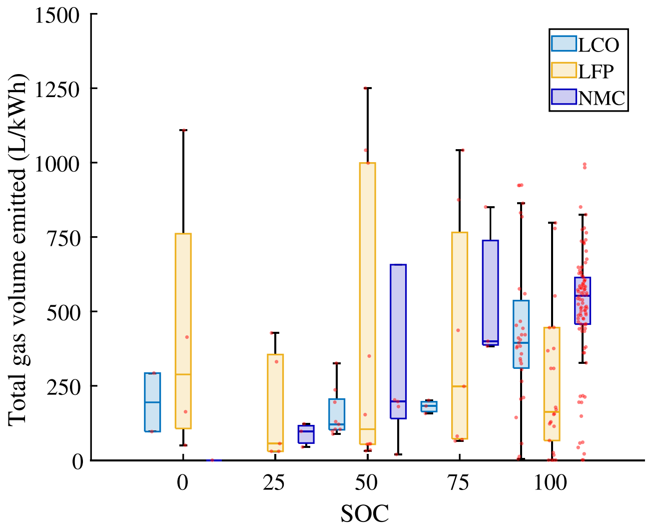


Fig. 7. The specific total amount of off-gas emitted from LIB failure at various SOC for air and inert atmosphere. (The number of values in each category are *SOC % [LCO, LFP, NMC]*: 0% [2, 4, 1], 25% [0, 5, 3], 50% [9, 10, 5], 75% [3, 7, 3] and 100% [31, 26, 98].).

For a clearer view of the median trends see Fig S6 which also presenting intermediate SOC as well as overcharge data. However, these additional SOC points typically only consist of one data entry, but from Fig S6 it can be seen there is a typical trend for LCO, LFP and NMC chemistries on overcharge to produce more off-gas than at 100% SOC. For the NCA chemistry there is negligible increase with overcharge.

It is of interest to determine if the severity of TR and off-gas production volume has changed over time with cell chemistry developments, i.e. with new additives or electrolyte compositions. Analysing the compiled data shows that on the whole there is no change in total specific off-gas production with time, see Fig. S7. LCO and NCA chemistries show an increase in the latter few years, but considering cell capacity, form, atmosphere and abuse type, no variables are determined to be influential. Hence, unknown cell material differences, differences in experimental setup or natural variation may be the cause.

4.3. Toxicity - HF and CO emissions

The total emission of HF and maximum emission rate is presented in Fig. 8, both of which increase with battery capacity. From this, it can be seen that the smallest cells release 0.01 g to 1 g of HF while larger cells release 0.1 g to 100 g and packs/EVs release kilogrammes of HF. The majority of cells studied are of LFP chemistry while NMC cells and EVs are studied to a lesser extent. The emission rates are less reported range from 10^{-4} g/s to 1 g/s from cell to EV scale (excluding HF release from air-conditioning).

The average HF emissions for LFP and NMC tests over various SOC is presented in Fig. 9 (note most of this data is related to cells as there is only one non-cell data point in the 100% SOC category). From this it is clear that the LFP chemistry typically releases over ten times more HF than the NMC chemistry normalised against battery capacity (50 g/kWh to 100 g/kWh for LFP vs <10 g/kWh for NMC). LFP cells show a slight downward trend in emissions as SOC increases (100 g/kWh at 0% SOC to 50 g/kWh at 100% SOC), due to higher TR temperatures reached (see Section 2.3), but NMC do not. However, due to the large variation in results there is little certainty that higher SOC will have lower emissions than lower SOC.

Note that there is limited data for LMO, NCA and LCO cells, although at 100% SOC LMO, NCA and NMC/LMO cells emit approximately 60 g/kWh, while LCO emit 15 g/kWh. LMO cells show a negative trend with SOC, while LCO do not show any trend.

Fig. 10 shows the maximum HF emission rate given SOC normalised against battery capacity. This shows that NMC cells have an increased rate with SOC (0.1 g/(s kWh) to 0.7 g/(s kWh)) while LFP do not. It also shows NMC cells have a much greater rate at larger SOC (0.7 g/(s kWh) for NMC vs 0.1 g/(s kWh) for LFP). This is attributed to the greater severity and strong SOC dependence of NMC failure.

The total emission of CO and maximum emission rate is presented in Fig. 11, showing both increase with battery capacity (most of the data is from cells, only four and two points at 25% and 100% SOC are not cells for LFP). Comparing Fig. 8 and Fig. 11 it can be seen that there is approximately an order of magnitude more CO emitted than HF given battery capacity, with rates also larger. A more detailed analysis of the CO emissions with SOC shows that at 100% SOC batteries with an NMC chemistry emit 10 times more CO specific to battery capacity than the LFP chemistry (172 g/kWh for NMC vs 19 g/kWh for LFP). Further, the CO emission of NMC batteries is two orders of magnitude greater than HF emissions, while for LFP the emissions are on the same order of magnitude. NMC batteries show a tendency to release more CO with increased SOC (10 g/kWh to 172 g/kWh for 25% to 100% SOC), while LFP batteries show a slight overall downward trend but there are unexpectedly low values at 25% and 75% SOC. This discussion has so far considered air and inert atmosphere data together. Fig S8 compares the results for LFP and NMC chemistries under both atmospheres and shows no statistical difference. As with the total volume (see Section 4.2), assuming composition is independent of atmosphere, the increase in total CO amount in NMC cells is both due to the chemistry and cell form leading to greater gas production.

4.4. Gas composition

A comparison of gas composition for each major chemistry over various SOC would be ideal. However, due to limited data only meaningful comparisons can be made for LFP and NMC at 100% and 50% SOC in air and 100% in an inert atmosphere. Results from tests in an inert atmosphere are considered as they simulate a scenario where oxygen is limited, such as in a sealed pack. Therefore, the gas composition before combustion can be determined, allowing for a truer assessment of off-gas hazards. Results for LFP and NMC in air at 100% SOC are presented in Fig. 13, other LFP and NMC results along with limited data for LCO and NCA is presented in Fig. S9 and Fig. S10. In these figures, *electrolytes* (Elect.) contains DMC, DEC, EMC and EC; *organic compounds* (org. comp.) contains ethanol, methanol, DME and methyl formate; *F containing compounds* (F comp.) is anything containing fluorine (including HF); and *other* is anything not listed in the graph or these categories. Note, due to a lack of compositional analysis tests in the literature concerning HF in LIB off-gas, only minimal data is available on HF as a fraction of the total gas. As such, there are fewer data points related to HF in the compositional analysis here than in the analysis of absolute HF production (Section 4.3).

For LFP at 100% in air (see Fig. 13), on average, the major component of the off-gas is H_2 (36%), then CO_2 (25%), CO (12%) and THC (11%). For NMC in similar conditions CO_2 (36%) is the major component, then CO (25%), H_2 (20%) and THC (12%). The greater CO and CO_2 generation by NMC is attributed to the tendency of NMC to lead to fires in air. Note, in previous works, non of the studies in air were set-up to record the emissions of electrolyte. Furthermore, there is no correlation of composition (percentage of species CO, CO_2, H_2 or THC) with battery capacity, see Fig. S11.

Consider 50% SOC in air for LFP and NMC (see Fig. S9(a)) there is no meaningful difference in results when compared with 100% SOC (Fig. 13). Comparing atmospheres (see Fig. S9(b)), we see that there is a greater variation in CO_2 percentage for LFP and greater H_2 generation than in Fig. 13. These results also show that electrolyte vapour is emitted to a small percentage, as well as O_2 to a lesser extent. From Fig. 13 it can be seen that H_2 is a significant flammability/explosion concern as it is typically present in a greater proportion than the THC content.

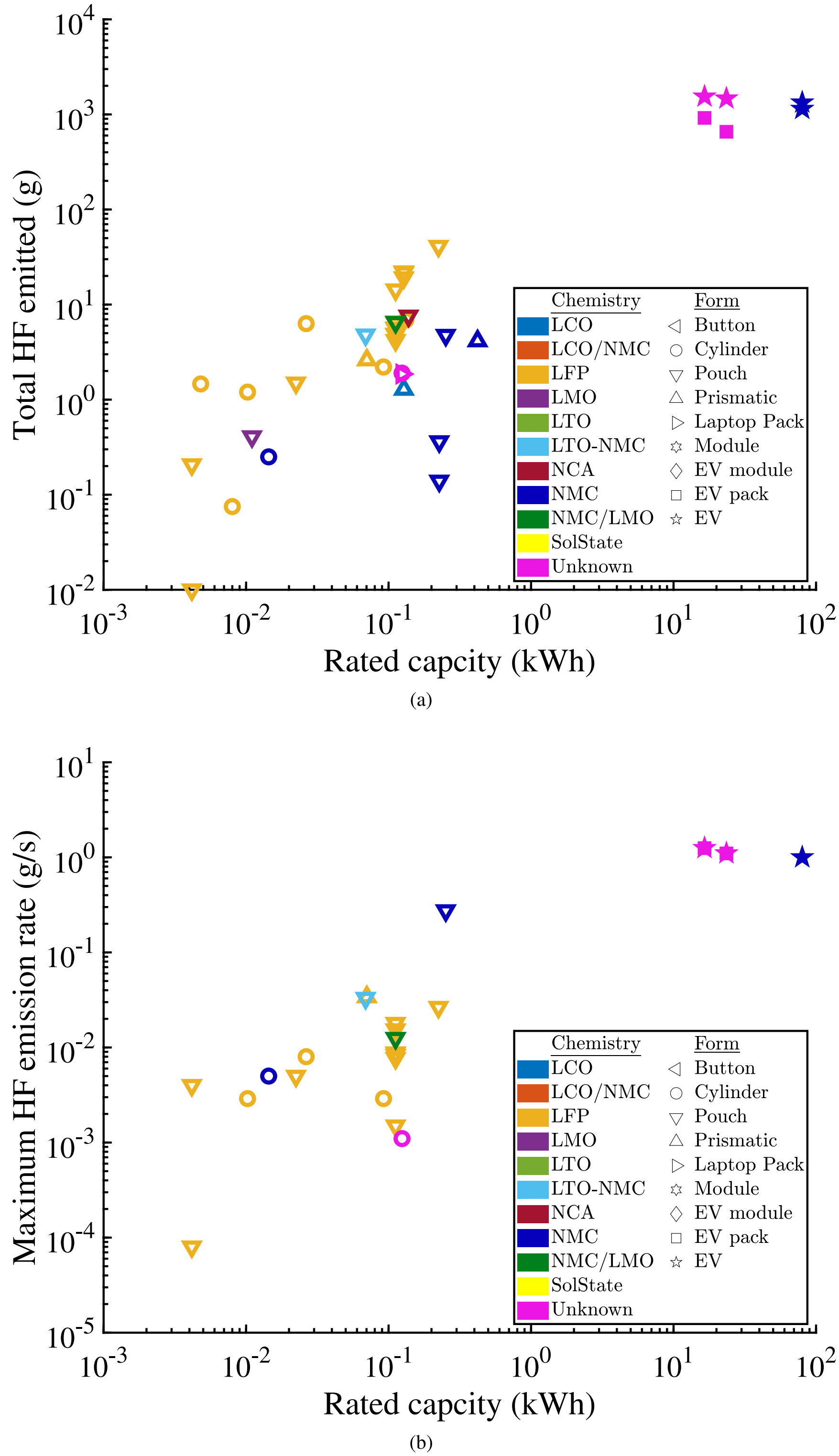
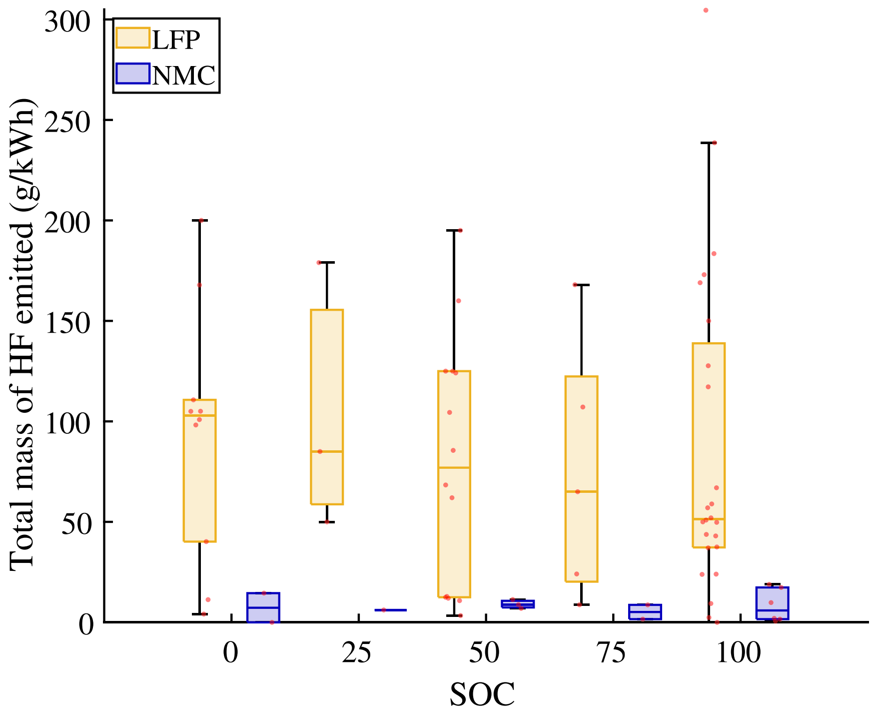


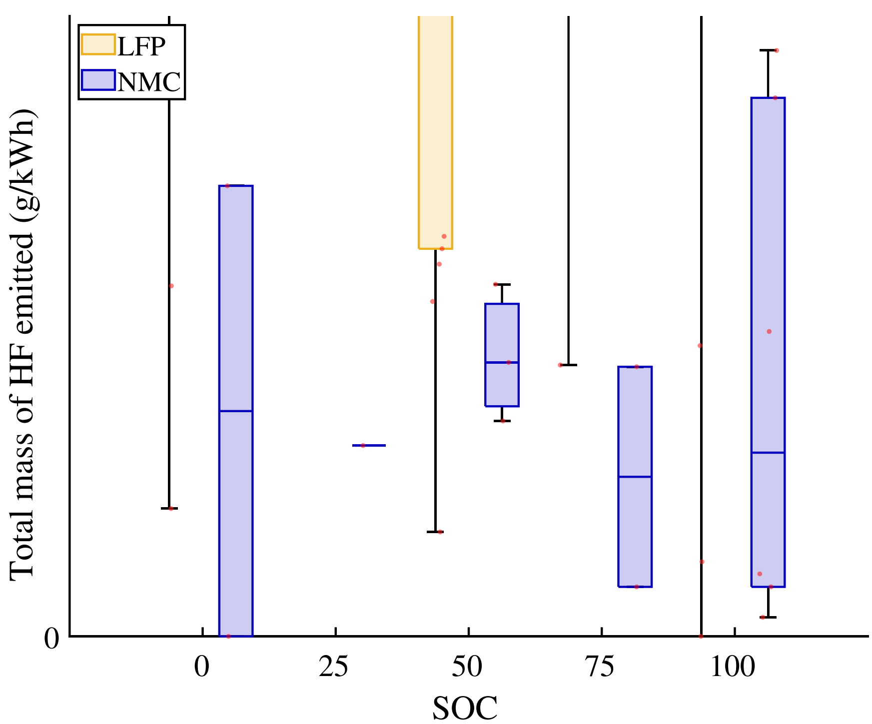
Fig. 8. HF emissions from LIB failure given rated battery capacity for batteries at 100% SOC considering all chemistries and form factors (a) total mass emitted, (b) maximum rate of emissions. Unfilled points are from tests conducted in air, grey filled points are from tests conducted in an inert atmosphere, coloured filled points are of an unknown SOC but assume 100% SOC for this plot.

It is also present in greater quantities for the LFP chemistry. The risk of H_2 content and also the role of cell chemistry on flammability is further discussed in Section 4.5.

As the emissions of gas species are interdependent, correlation plots are presented to understand the relation between the production of each gas, see Fig. S12 and Fig. S13. However, there is no consistent behaviour between chemistries or atmospheric conditions. This is attributed to the unpredictability of combustion occurrence, and the effect the test set-up has on the availability of oxygen to promote combustion i.e. if the system is open or closed and the working volume.



(a)



(b)

Fig. 9. (a) The specific total mass of HF emitted from LIB failure at various SOC in air, (b) enlargement of NMC data. (The number of values in each category are *SOC % [LFP, NMC]*: 0% [10, 2], 25% [3, 1], 50% [14, 3], 75% [5, 2] and 100% [24, 6].)

4.5. Discussion and recommendations

From Section 4.1 it can be noted that there is a lack of studies on the off-gassing of modules and packs. Addressing this in the academic community is important to understand how the behaviour of off-gassing and its composition changes with scale so that the change in hazards with scale can be properly assessed. However, the literature does study cell form evenly between the three main types (cylindrical, pouch and prismatic) and focuses on the two chemistries mainly used in automotive sector NMC and LFP. As such the literature is useful for the industrial community. Although the elemental ratio of NMC cells is reported more in recent years, a third of papers still do not.

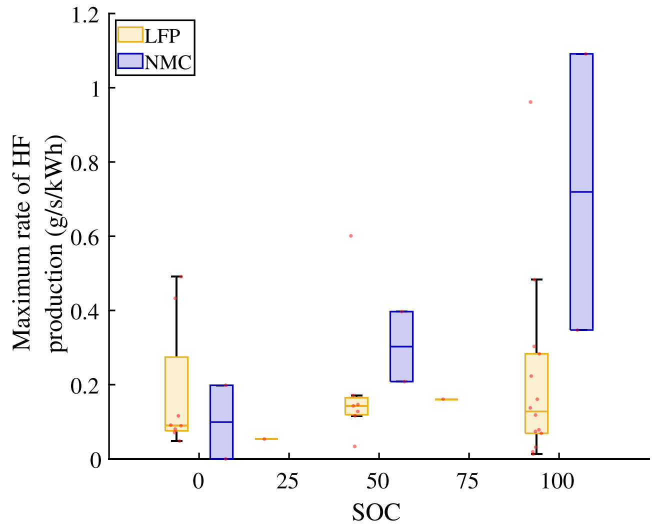


Fig. 10. The specific maximum rate of HF production from LIB failure at various SOC in air. (The number of values in each category are *SOC % [LFP, NMC]*: 0% [8, 2], 25% [1, 0], 50% [7, 2], 75% [1, 0] and 100% [14, 2].).

Hence, the academic community should encourage reporting of this to better understand the role of chemical composition of NMC on off-gas behaviour.

From the analysis in Section 4.2 it is clear that there is a strong positive correlation between off-gas volume and battery capacity across the entire range from Wh to kWh. However, the amount of gas produced specific to battery capacity is independent of battery capacity. NMC batteries do tend to produce more gas than other chemistries when considering all battery types. In general prismatic cells tend to produce more off-gas than pouch followed by cylindrical cells, even when considering chemistry. This could be caused by the large form factor having lower heat loss per unit volume leading to higher temperatures and increased decomposition. When considering separate cell forms, cylindrical LFP and NMC cells have similar medians and ranges, while LCO have a great median. For prismatic cell NMC produce less off-gas than LCO. However, there is limited data for cylindrical and prismatic LCO cells and also pouch and prismatic LFP cells which hinders comparison. Cylindrical cells and LFP chemistry show a slight tendency for greater variation in gas volume production.

As LFP are widely used in the automotive sector, more analysis of LFP pouch and prismatic cells at the scale of 10–100 Ah is crucial for hazard assessment between NMC and LFP batteries. Also, as the literature (see Section 2.6) has shown, it is difficult to scale cell TR behaviour to stack/module/pack TR behaviour. As such, comparisons of LFP and NMC batteries of a given capacity constructed of different cell forms need to be rigorously conducted to determine if there is any real difference in TR hazards, including gas hazards.

The amount of gas produced in air is not consistently more or less than that generated in an inert atmosphere, so the effect of the atmosphere on off-gas volume production is considered negligible. As is commonly suggested in the literature (Section 2.1), larger SOC typically leads to greater off-gas volumes while NMC LIBs generate more gas than LFP over all SOC. The variation within the data means that given a chemistry, a higher SOC may not lead to more gas, while LFP LIBs may produce as much as NMC LIBs. However, at SOC other than 100% and at overcharge there is significantly less data, typically less than 10 data points and only 1 for stages of overcharge (for each chemistry). Overcharge is a typical area of concern as it can occur undetected within battery operation. Hence it is critical to risk assessments to understand how the off-gas generation evolves with overcharge and should be a focus of the research community.

Table 3
Theoretical contaminated volume calculated from median HF and CO emissions for a 0.01 kWh battery.

Emissions at 100% SOC (g/kWh)		
Component i	NMC	LFP
CO	172	19
HF	6	52
Emissions at 0% SOC (g/kWh)		
Component i	NMC	LFP
CO	10[a]	34
HF	7	102
Contaminated Volume (m^3)		
SOC	NMC	LFP
100%	115	355
0%	51	695

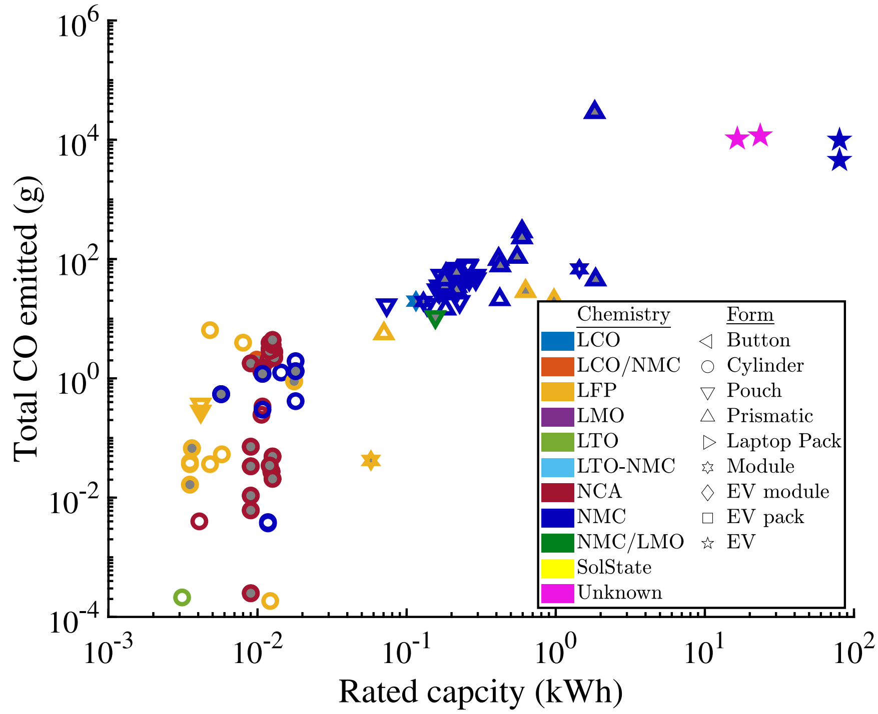
[a] Estimated from data at 25% SOC.

The toxic component analysis in Section 4.3 shows HF release from LFP cells is greater than from NMC over various SOC, with a median in the range of 60 g/kWh to 100 g/kWh for LFP versus less than 10 g/kWh for NMC. However, the rate of HF release is greater for NMC cells than LFP cells at higher SOC, due to the increased severity of TR of NMC versus LFP. LFP show the trend of less HF production at higher SOC due to increased temperature of TR, while NMC show no trend due to relatively high TR temperatures at all SOC. The release of CO is greater for NMC cells compared to LFP cells. Over 0% to 100% SOC the release is 11 g/kWh to 172 g/kWh for NMC compared to 34 g/kWh to 19 g/kWh for LFP. Although several studies have investigated the absolute HF production, few have done so as a fraction of the overall composition of the off-gas (see Section 4.4). This should be a consideration for the academic community to determine if there are any correlations of the fraction of HF to other off-gas species to complement the correlations of SOC and cell chemistry analysed in this work.

As the HF and CO production vary greatly with chemistry and SOC, the overall toxicity hazard has to be assessed considering the total amounts of all toxic components. This can be done by calculating the theoretical contaminated volume (m^3) according to Eq. (1) [50]. Where m is the mass (mg) of the toxic component i which has an exposure limit value EL (mg/m^3). The short term exposure limits (in the UK) for HF and CO are 1.5 mg/m^3 and 23 mg/m^3, respectively [54]. With this and the median HF and CO emissions for NMC and LFP at 0% and 100% SOC (see Figs. 9 and 12), Table 3 presents the calculated contaminated volume assuming a 0.01 kWh battery (this is the scale of a single cylindrical cell). Note median values are used as there are limited sources that reports both CO and HF emissions together for all four cases.

$$V_{contaminated} = \sum_{i=1}^{n} \frac{m_i}{EL_i} \quad (1)$$

From Table 3 it is shown that LFP batteries are significantly more toxic than NMC batteries when considering both major toxic components, especially at 0% SOC. This is due to the very low exposure limit of HF and the higher emissions of HF by LFP batteries. However, LFP batteries are nearly half has hazardous at 100% SOC than at 0% SOC as both HF and CO reduce at higher SOC. In comparison, NMC batteries are over twice as toxic at 100% SOC than 0% due to the large increase in CO emissions. Further, the lowest emissions from a single cell (approximately 0.01 kWh) are enough to full a single car garage or 20 ft shipping container. But at a large cell or module scale (where simultaneous burning is possible) contaminated volumes would be 10 and 100 times greater respectively. From this, LFP batteries can be said to be more toxic than NMC (in absolute terms) even though they produce on average less off-gas overall. However, the suffocation (from CO_2 emissions) and flammability hazards have to also be considered, discussed below.



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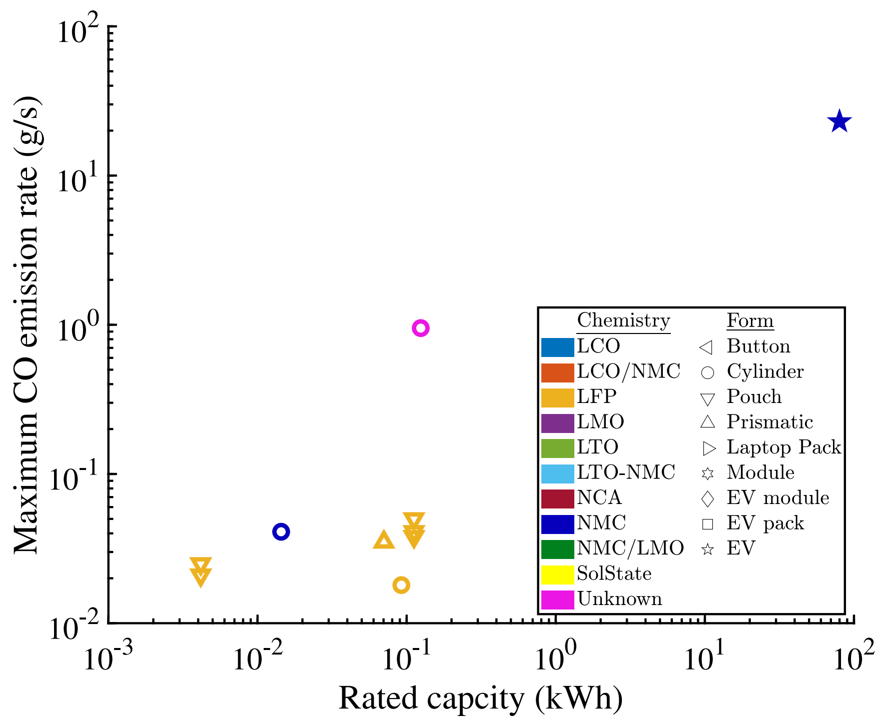
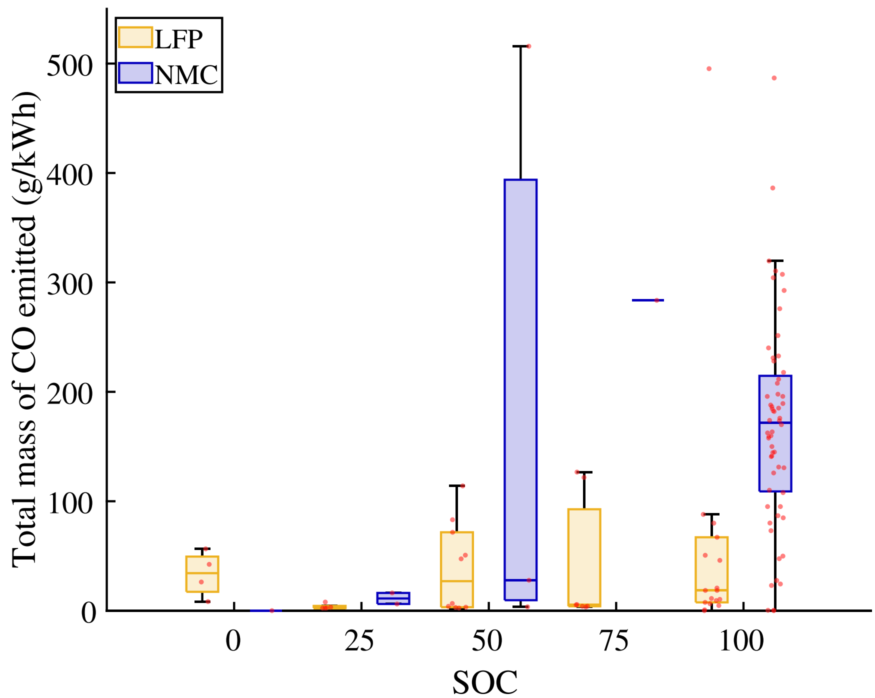


(b)

Fig. 11. CO emissions from LIB failure given rated battery capacity for batteries at 100% SOC considering all chemistries and form factors (a) total mass emitted, (b) maximum rate of emissions. Unfilled points are from tests conducted in air, grey filled points are from tests conducted in an inert atmosphere, coloured filled points are of an unknown SOC but assume 100% SOC for this plot.



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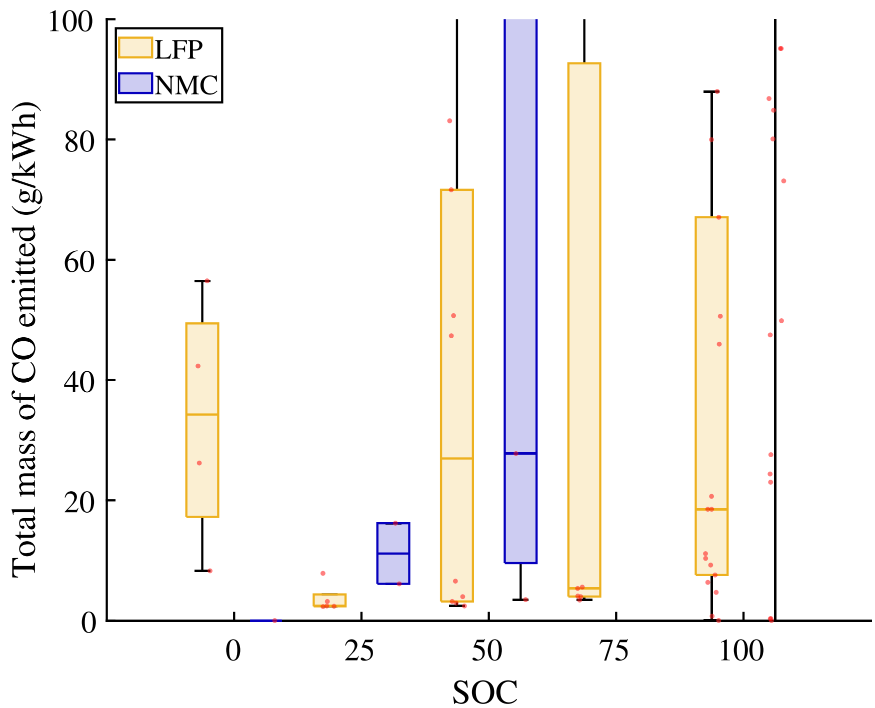


(b)

Fig. 12. (a) The specific total mass of CO emitted from LIB failure at various SOC in air, (b) enlargement of LFP data. (The number of values in each category are *SOC % [LFP, NMC]*: 0% [4, 1], 25% [5, 2], 50% [10, 3], 75% [7, 1] and 100% [18, 60].)

From the gas composition results of Section 4.4 it is shown there is a lack of data quantifying electrolyte solvent emissions, especially in air, as experiments are not set-up to detect it. This should be address as the electrolyte vapour is considered to be a significant flammability hazard. Further, tests set up should be assessed to ensure it does not affect results, i.e open/closed system limiting combustion. From analysis of the off-gas composition, it is found that the LFP chemistry releases more H_2 than NMC on average, while more CO is emitted by NMC with similar hydrocarbon contents in both. However, it is difficult to assess the overall flammability hazard from this data. Hence, to assess the flammability hazard of each chemistry the lower flammability limit (LFL) of the off-gas mixture is calculated. This is done according to the methods in Ref. [105] accounting for the dilution of the off-gas by the CO_2 generation. The LFL of each component (CO, H_2 and hydrocarbons

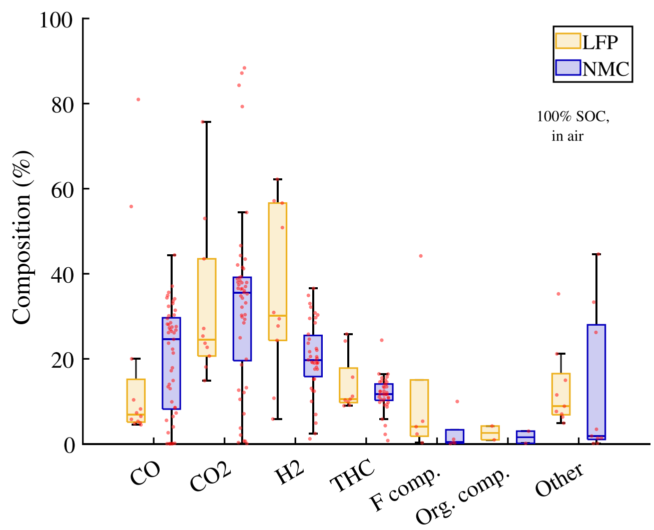


Fig. 13. Gas composition for LFP and NMC abused LIBs at 100% SOC in air. (The number of values in each category are *Gas [LFP, NMC]*: CO [12, 49], CO_2 [10, 49], H_2 [10, 39], THC [9, 39], F containing compounds [5, 5], organic compounds [2, 2] and other [9, 9].

present) are from data tables in Ref. [106]. Further detail of the LFL calculation methodology (including a table of LFL values for individual species) is given in the supplementary material.

Fig. 14 presents the calculated LFL. It can be seen that the LFP chemistry has a lower LFL (6.2%) compared to NMC (7.9% to 9.2%). This is attributed to LFP having a lower fraction of CO (which has a large LFL) and CO_2 (which dilutes the mixture), whilst having higher H_2 fractions, compared to NMC. The large range of LFL for NMC in air is attributed to the large range in CO and CO_2 production related to the variability in combustion of the off-gas leading to in/complete combustion products. Given the median LFL (Fig. 14) and gas volumes produced (Fig. 6) in an inert atmosphere then LFP batteries would breach their LFL in a volume 18% smaller than NMC cells (calculated assuming the gas is only comprised of CO_2, CO, H_2 and hydro carbons). Hence, LFP batteries present a greater flammability hazard even though they (specifically cells) show less occurrence of flames.

As noted previously, CO_2 is not considered as a toxin, but in high quantities it presents a suffocation hazard. However, Fig. 15 shows that the contaminated volume from a 0.01 kWh battery (where the short term exposure limit of CO_2 is 27 400 mg/m^3) is minimal. Even at the 1 kWh scale the hazardous volume would still be less than 10 m^3, so the suffocation hazard is low relative to the toxicity hazard.

As noted above, LFP cells show a tendency for a lower LEL but this does not account for the presence of solvents (due to lack of available data). However, as shown by Fernandes et al. [48] up to 60% of the off-gas emission can be made up of electrolyte solvents when no venting fire occurs. This will also be true for other chemistries, however, the important factor here is that due to the lower TR temperature of LFP cells it is more likely that the vent gas is emitted without combustion. This results in a greater likelihood of vapour cloud emission and accumulation, leading to an increased risk of vapour cloud explosions for LFP batteries compared to NMC. This needs to be stressed in safety and risk assessments given the general belief that LFP cells are "safe" or "the safest" in public media [e.g.107–110]. This "safest" chemistry belief is based on typical abuse tests (overheat, penetration, etc [111]) due to LFP having lower maximum temperatures and heat generation or the absence of visible sparks and flames [112–114]. However, there are many instances of LFP-based EVs under TR and emitting vapour clouds [6,10], especially in the Chinese market where LFP dominates [115]. Additional to this is the emission of toxic substances that also present a further hazard. As such, it is unwise to categorise the safety of a battery system based on the abuse test of cells that do not account for the explosion of the off-gas (and its toxicity) or the influence of the battery system design on failure behaviour. Therefore, there should be a focus within the battery community to provide a holistic assessment of battery safety considering stability and thermal, fire/explosion and toxicity hazards.

5. Conclusion

The off-gas from Li-ion battery TR is known to be flammable and toxic making it a serious safety concern of LIB utilisation in the rare event of catastrophic failure. As such, the off-gas generation has been widely investigated but with some contradictory findings between studies. However, no work has comprehensively analysed the available literature data to determine how the chemistry, SOC, scale/capacity and form affect gas volume production, toxicity and flammability. Hence, in this work we conducted a detailed meta-analysis of 60 papers to investigate the most influential parameters and the probable off-gas characteristics to determine what kind of battery would be least hazardous.

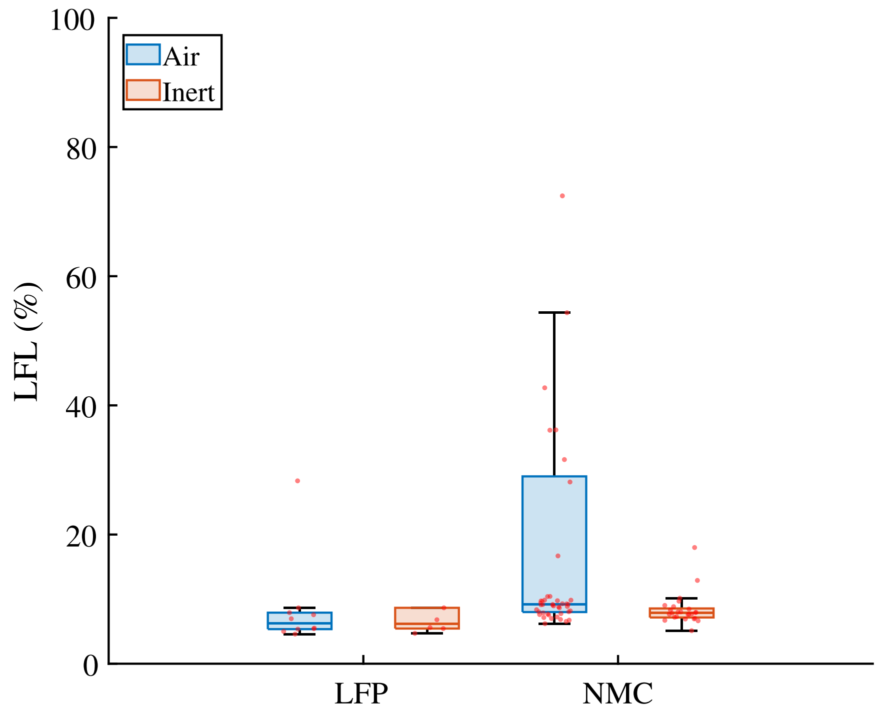
From the analysis, it is found that LFP and NMC batteries are the most studied, aligning with industries tendency towards theses chemistries. The amount of gas produced scales linearly with capacity, however the specific gas production (L/kWh) shows no trend with capacity. NMC LIBs produce more off-gas than other chemistries (LCO 394 L/kWh, LFP 126 L/kWh, NCA 169 L/kWh, NMC 519 L/kWh), while prismatic cells also tend to generate larger off-gas volumes (cylindrical 156 L/kWh, pouch 502 L/kWh, prismatic 598 L/kWh). Also, a larger SOC does lead to greater average specific off-gas volumes specifically for NMC and LCO batteries, however there is significant variation in results.

While NMC batteries release more gas than LFP, LFP batteries are significantly more toxic than NMC ones in absolute terms. Toxicity varies with SOC, for NMC batteries the contaminated volume doubles from 0% to 100% SOC while for LFP in halves. The composition of off-gas on average is very similar between NMC and LFP cells, but LFP batteries have greater H_2 content while NMC batteries have a greater CO content. To assess the fire hazard the LFL limit of the off-gasses is compared. The LFL for LFP and NMC are 6.2% and 7.9% (in an inert atmosphere) respectively. Given the LFL and the median off-gas volumes produced, LFP cells breach the LFL in a volume 18% smaller than NMC batteries. Hence LFP presents a greater flammability hazard even though they show less occurrence of flames in cell TR tests.

Also, from this work it is found that significant improvements in research can be made. To advance the understanding of off-gas further, for improved battery safety, it is recommended that:

1. the electrode elemental ratio and electrolyte composition of cells are reported to better compare NMC results and understand the affect of electrolytes;
2. LFP pouch and prismatic cells at the scale of 10–100 Ah to be studied to address the gap in data at this scale, so that like-for-like comparisons between high energy LFP and NMC cells can be made;
3. tests at module and pack level should be conducted to understand how the hazards scale with battery size;
4. the off-gas generation is studied at other SOC other than 100% and especially at overcharge to accurately determine how toxicity and flammability hazards vary; and
5. the experimental set up is designed to ensure the detection/quantification of common electrolyte solvents to determine when and how much is emitted as a vapour and hence determine the additional flammability hazards.

Finally, this work provides a critical resource to the battery community that can be used for the risk assessment of LIB TR fire, explosion and toxicity hazards. This is aided by supplying the compiled literature data in a raw format that is readable and editable to allow independent and ongoing analysis by interested/relevant parties.



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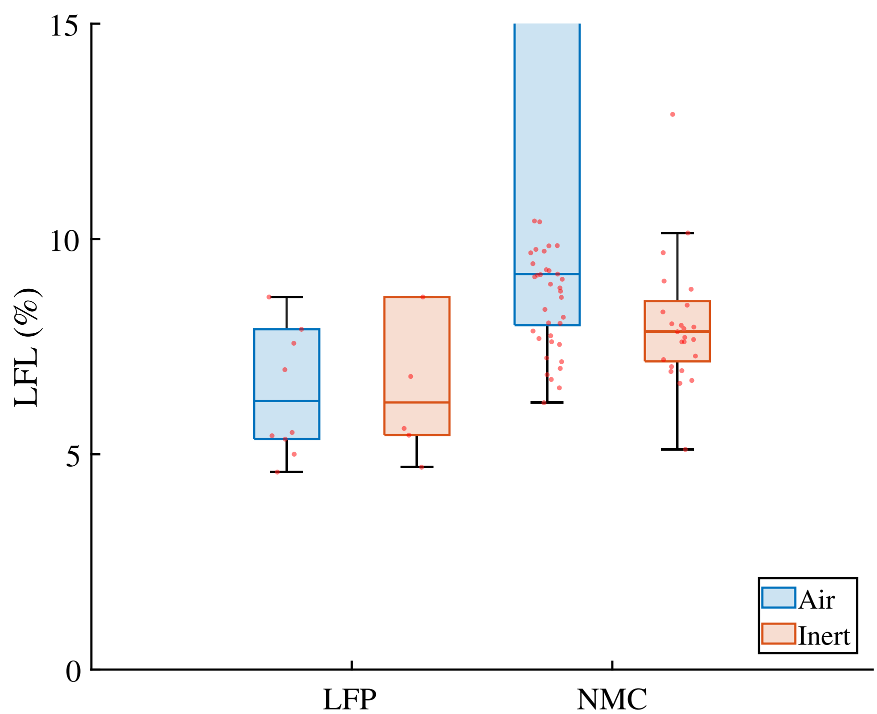

(b)

Fig. 14. (a) Calculated lower flammability limit considering CO, H_2 and hydrocarbons diluted by CO_2 (b) enlargement of data. (The number of values in each category are *Chemistry [Air, Inert]*: LFP [10, 6] and NMC [49, 25].)

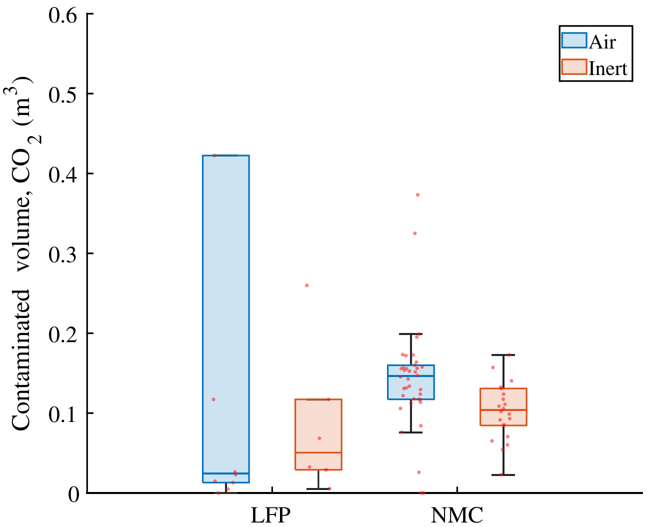

Fig. 15. Contaminated volume from CO_2 assuming 0.01 kWh battery. (The number of values in each category are *Chemistry [Air, Inert]*: LFP [10, 6] and NMC [38, 22].).

CRediT authorship contribution statement

Peter J. Bugryniec: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Erik G. Resendiz:** Writing – review & editing, Data curation. **Solomon M. Nwophoke:** Writing – review & editing, Data curation. **Simran Khanna:** Writing – review & editing, Data curation. **Charles James:** Writing – review & editing, Data curation. **Solomon F. Brown:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data is made available through the CSV files available as supplementary material.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.est.2024.111288.

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ATTACHMENT 7

PARTIAL COPY OF REPORT TITLED "*EXPERIMENTAL STUDY ON THERMAL RUNAWAY AND FIRE BEHAVIORS OF LARGE FORMAT LITHIUM IRON PHOSPHATE BATTERY*".

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Experimental study on thermal runaway and fire behaviors of large format lithium iron phosphate battery

Pengjie Liu[a], Yongqi Li[b], Binbin Mao[a], Man Chen[b], Zonghou Huang[a], Qingsong Wang[a]

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Highlights

- The thermal runaway and fire behaviors of 243 Ah $LiFePO_4$/graphite batteries are investigated.
- The temperature characteristics, voltage, mass loss, heat release rate, total heat release and gas release are quantified.
- The effects of SOC and flame on the thermal runaway process of individual cell are analyzed.
- The relationship between TR and fire behaviors is revealed.

Abstract

With the increase of large-scale lithium ion batteries (LIBs), the thermal runaway (TR) and fire behaviors are becoming significant issues. In this paper, a series of thermal abuse tests were conducted on 243 Ah LIBs in two conditions using an in situ calorimeter. One is “ignited test (case 1)” and the other is involving in “unignited test (case 2)”. The flammable substances were ignited by an igniter at the safety venting (SV) under case 1 and the burning behaviors of LIBs were investigated comprehensively from the aspect of temperature characteristics, voltage, mass loss, heat release rate (HRR), total heat release (THR) and gas release. In case 2, the venting behaviors were characterized and the effects of SOC and flame on the TR process of individual cell have also been investigated. The HRR and THR can reach 88.6 kW and 19530.6 kJ, respectively. A real-scale scenario of 50 m^3 is used to assess the gas toxicity. The CO and HF have larger toxicity than other gases. The results indicate that fire hazards of LIBs increase with the SOC. The characteristic temperature is determined by the inner reactions, and the flaming combustion accelerates the TR progress. The relationship between TR and fire behaviors is revealed from the aspects of electrolyte vaporization, gas generation and venting. It is analyzed that the fast exothermic processes during TR are the main causes that lead to the jet fire. Several proposals are advanced to improve the safety application of LIBs.

Introduction

Lithium ion batteries (LIBs) are nowadays recognized as the most appropriate technology for energy storage, and are increasingly applied in automotive, stationary and aeronautic since they possess high energy density and excellent cycle-life [1]. While seeking ways for performance optimization and cost reduction of LIBs, the safety risk remains a major obstacle for marching the large-scale application. The fire and explosion accidents of LIBs occurred frequently due to the highly energetic and flammable materials [2]. Failure of a single battery can lead to physical and chemical reactions involving these components (cathode, anode, electrolyte and separator) that result in the generation of excessive heat and gas. When working outside the stability domain (in terms of temperature), the highly exothermic reactions cause a rapid self-heating of cells-a condition is known as thermal runaway (TR) with associated events such as smoke generation, jet fire and explosion [3].

TR can be initiated by thermal abuse, electrical abuse and mechanical damage. To investigate the TR mechanism, numerous researches have been carried out at cell constituents and whole-cell level [4]. Calorimetry measurements of cell components include the use of C80 micro calorimeter and different scanning calorimetry (DSC) to elucidate the thermal property of these materials [5], [6]. Experimental techniques of a single cell scale include the use of accelerating rate calorimetry (ARC), oven tests, Copper Slug Battery Calorimetry (CSBC) and cone calorimetry to identify temperature where exothermic reactions occur and measure heat release of internal reaction and external combustion [7], [8], [9], [10]. For lithium iron phosphate cells (LFP), the major thermal events taking place during TR are commonly as follows: (1) solid electrolyte interphase (SEI) decomposition; (2) the reactions between electrode and solvent (3) separator melting; (4) the decomposition of LFP cathode and electrolyte [11]. The TR process is closely related to fire behaviors of LIBs caused and governed by these thermal events. The relationship between TR and fire behaviors deserves further investigation, because it is still unclear that why some cells result in multiple jet fire events while others do not.

The fire triangle is necessary to catch a fire for LIBs. Typical igniter/heater reported during LIB fires including sparks and heat produced by exothermic reactions. The sparks are probably derived from the cathode materials and lithium salts projected from cells under high pressure [12]. The combustible materials are mainly the electrolyte and separator, accounting for 80% of the total heat release (THR) of flaming combustion [13]. The available oxygen is produced by the decomposition of cathode or from the air. For LFP cells, the strong covalent P-O bonds inhibit the evolution of oxygen and vastly limit the amount of heat produced that can in turn reduce the possibility of self-ignition and the severity of LIBs fire [14]. Despite the significant safety advantages, there still exists high fire risks with external ignition sources and more unignited jet flow occurs over that of other Li-ion chemistries.

There also have been some investigations concerning fire behaviors of LIBs, which mainly focused on the influence of various factors on combustion features of LIBs, including state of charge (SOC), state of health (SOH), cell composition and environment pressure [15], [16], [17]. Ribiere et al. [13] performed fire tests on 2.9 Ah $LiMn_2O_4$ (LMO) batteries and found that the fire severity increased with the increasing SOC. Mao et al. [17] investigated burning behaviors of 18650-type $Li(Ni_{0.5}Co_{0.2}Mn_{0.3})O_2$ (NCM) LIBs, and proposed that the heat release rate (HRR) depended significantly on SOC. Except for the huge heat released, the fire effluents of LIBs are more serious in some circumstances. Larsson [18] and Lecocq [19] conducted combustion tests to assess the gas products toxicity and revealed that the toxicity is influenced by the SOC and the nature of the salts. According to their studies, it is believed that SOC is the main factor and directly determines the fire load, jet fire times and gas toxicity. All the studies mentioned above mainly focused on small-scale batteries. However, the use of large-sized LIBs is increasing due to the development of electric vehicles (EVs) and energy storage systems (ESS). Increased capacity leads to the increasing fire risks due to more energetic substances. Hence there is a strong demand to investigate the fire behaviors of large-scale LIBs and understand the mechanisms behind it. Huang and Ping et al. [20], [21] performed full-scale burning tests to study the fire behaviors of 50 Ah $Li(Ni_xCo_yMn_z)O_2/Li_4Ti_5O_{12}$ batteries and 50 Ah $LiFePO_4$/graphite battery packs. Peng et al. [22] systematically studied the thermal and toxic hazards of a 68 Ah pouch LIBs. These studies mainly focused on the gas toxicity and thermal hazards. However, the mechanisms behind various fire behaviors were not analyzed, and over 100 Ah cells of ESS have been investigated only rarely in previous researches.

The effect of flame on the TR process attracts much attention due to huge heat released. Feng et al. [23] proposed that the fire has little impact on TR, while Rengaswamy et al. [24] found that the fire plays a major role in TR propagation. In this study, the effect of flame on TR of cells with different SOCs has been quantitatively investigated. Additionally, the qualitative and quantitative analysis of the burning behaviors and venting behaviors is crucial for both risk analysis and protection design. Systematic studies for TR and fire behaviors help us know the mechanism of jet fire more deeply. Furthermore, the current work has been compared with the previous studies to better understand the combustion features of large scale LIBs.

In this paper, two series of thermal abuse tests on the 243 Ah prismatic $LiFePO_4$/graphite LIBs were performed. One is “ignited test (case 1)” and the other is involving in “unignited test (case 2)”. The flammable substances were ignited by an igniter at the safety valve open under case 1 and the burning behaviors of LIBs were investigated comprehensively from the aspect of temperature characteristics, voltage, mass loss, HRR and gas release. In case 2, the venting behaviors were characterized by the above dynamic parameters except for HRR. To understand the mechanism of jet fire, the relationship between TR and fire behaviors is revealed from the aspects of electrolyte vaporization, gas generation and venting. The effects of SOC and flame on the TR process of individual cell have also been investigated to create a comprehensive understanding of LIBs fire. Several proposals for detection and protection of TR are advanced to improve the safety application of LIBs.

Section snippets

LIB samples

For this study, commercial prismatic LIBs were tested due to their widespread use in the energy storage power station. These LIBs employ $LiFePO_4$/graphite as their electrodes, which have nominal capacity and voltage of 243 Ah and 3.2 V, respectively. The physical dimension is 173 mm in length, 71 mm in width and 200 mm in height. The 243Ah battery contains two pouch cells connected in parallel. Each battery is equipped with a burst disc and one safety vent port at the middle of the two tabs...

Burning behaviors in case 1

Fig. 3 presents the representative burning behaviors corresponding to various timestamps during the combustion process. For the LIBs with different SOCs, the overall burning process was basically consistent, while there were some differences between them as well. According to the manifestation of the fire behaviors, the process can be mainly classified into the four stages: (I) venting and ignition, (II) stable combustion, (III) jet flame and (IV) abatement and extinguishment. Note that no jet....

Conclusions

A series of thermal abuse tests were conducted on 243 Ah LIBs with different SOCs in two conditions. One is “ignited test (case 1)” and the other is involving in “unignited test (case 2)”. In case 1, some combustion dynamic parameters were recorded to help us reveal the burning behaviors more deeply. In case 2, the venting behaviors were characterized and the effects of SOC and flame on the TR process of individual cell have also been investigated. The major conclusions are summarized as.....

CRediT authorship contribution statement

Pengjie Liu: Investigation, Conceptualization, Methodology, Formal analysis, Writing - original draft, Data curation. **Yongqi Li:** Validation, Data curation. **Binbin Mao:** Writing - review & editing, Resources, Data curation. **Man Chen:** Writing - review & editing, Validation. **Zonghou Huang:** Writing - review & editing, Resources. **Qingsong Wang:** Conceptualization, Methodology, Writing - review & editing, Supervision, Visualization, Funding acquisition...

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper...

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J. Power Sources (2018)

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Thermal runaway and fire behaviors of large-scale lithium ion batteries with different heating methods
J. Hazard. Mater. (2019)
There are more references available in the full text version of this article.

ATTACHMENT 8

EXCERPT FROM 1993 EPA STUDY OF HYDROGEN FLUORIDE.

550R93001

Hydrogen Fluoride Study

Final Report

Report to Congress

Section 112(n)(6) Clean Air Act As Amended

systems.[7] For example, a Mobil refinery is evaluating an ion mobility detector as a point sensor to detect HF at a concentration of 10 to 20 ppm. The same facility is testing the use of silicon detectors to trigger deluge systems at HF concentrations of 200 to 400 ppm.[8] Amoco has installed throughout their alkylation units several types of detectors including open path infrared absorption detectors and thermal imaging cameras.[9]

7.3 General Industry Practices to Mitigate HF Releases

Mitigation measures are designed to reduce the quantity or concentration of HF released after a loss of containment, before the HF migrates off-site, reducing the potential for chemical exposure to workers and the general public. Effective mitigation measures are specific to the site, location conditions, process characteristics, and scale of operation. For example, a release of superheated liquid HF is likely to result in an aerosol vapor cloud and, therefore, diking would not be an effective mitigation technique. Alternatively, a release of low pressure subcooled HF liquid may form a liquid pool. Diking and vapor suppression may be useful; however, liquid HF vaporizes very rapidly.[10]

Because HF can be released as a vapor or as a liquid, mitigation systems have been developed to address both atmospheric releases and liquid spills. The series of Goldfish tests in 1986 (see Chapter 9 for additional discussion) showed that for accidental releases of HF at alkylation unit temperature and pressure, and at the ambient conditions at the test facility, the HF flashed and generated a denser-than-air cloud. The cloud also had a high aerosol and cold HF vapor content with no liquid drop-out observed. In 1988, another series of HF tests called the Hawk HF Test Series (also discussed in Chapter 9) was devised to measure the effectiveness of water sprays. For atmospheric releases of HF gases or vapors, the tests indicated that water spray systems could be effective in reducing airborne HF. At water to HF ratios of 40 to 1, water sprays have been documented as reducing the concentration of HF in the air by up to 90 percent.[11,12] The following is a summary of the mitigation systems used in the HF industry.

7.3.1 Water Spray Systems

Following the Goldfish Test series in 1986 which examined the source and dispersion characteristics of HF released under alkylation unit conditions, the test participants formed the Industry Cooperative HF Mitigation/Assessment Program (ICHMAP). This group of 20 companies in the chemical and petroleum industries then sponsored and conducted a water spray test program in 1988 called the Hawk Test series. Approximately 80 experiments were conducted in a flow chamber with the release source a horizontal jet of HF pointed at the mitigation device. These experiments considered variations in wind speed, humidity, acid type, and the mitigation device.[13]

These tests demonstrated that high HF removal rates could be achieved under controlled ideal conditions; however, the rate could also be reduced by non-optimal interaction between the cloud and the spray. Further, a high ratio of water to HF would not guarantee effectiveness of a water mitigation system, and the issue of scale-up from the experimental design to a plant-scale design system needed further work. To address these issues a computer program to model water spray removal was developed to assess overall effectiveness of a water spray given facility-specific configuration and conditions. This model called HFSPRAY was verified against the 1988 Hawk Test experiments and found to agree well with both field test data and wind tunnel data.[14]

A water spray system can be used to mitigate a major release of HF. An alternative to water, although rarely used, is a mild alkaline solution such as ammonia water or a sodium carbonate solution. A water spray system may include several types of water spray subsystems. A fire water subsystem consists of a stationary dense water stream that is used primarily for fighting fires and could also be used to knock down HF vapors. Other remotely operated or portable water monitors are primarily used to knock down HF vapors. In contrast to the water monitors, a water deluge

ATTACHMENT 9

CAUSES OF THERMAL RUNAWAY AND MISCONCEPTIONS ABOUT LITHIUM BATTERY SAFETY.

WHY DOES THERMAL RUNAWAY OCCUR?

Thermal runaway events occur frequently because they result from many different factors. One cause is manufacturing error; for instance, if the separator barrier between the anode and cathode is defective, then an internal short circuit occurs and thermal runaway is immediately initiated. Other manufacturing errors will result in impaired Battery Management Systems (BMSs) which can fail to prevent battery overcharging which in turn damages the separator barrier; when sufficient damage is done, a short circuit will occur and thermal runaway will initiate. BMS failures can also cause battery cells to overdischarge (which drops the cell voltage to a level below the manufacturer's recommendation); if this occurs multiple times, thermal runaway can be triggered when the cell is recharged[1]. Manufacturing errors can also result in flawed cooling systems which fail to maintain proper battery temperature and thus cause thermal runaway. Manufacturing defects are perhaps the most insidious causes of thermal runaway because they are generally invisible and undetectable.

Manufacturing defects are also frighteningly common. Clean Energy Associates (CEA) conducted inspections at 64 percent of "Tier 1" lithium-ion BESS manufacturers around the world (in the United States, South Korea, India, Viet Nam, and China) and found a very high incidence of manufacturing deficiencies[2]. Among other things, the CEA study cited substandard quality control procedures, defects in upstream components that were not caught during quality checks, poorly welded wiring connections, charging/ discharging failures, structural deformations, and "abnormally large temperature and voltage variations among battery cells". The study also found that 26% of the BESS systems that were inspected had deficiencies related to the fire detection and suppression system and 18% had deficiencies related to the thermal management system. Notably, each of these deficiencies (whether related to wiring, welding, structural deformations, or system controls) can cause a thermal runaway event.

Another cause of thermal runaway is the failure of a mechanical cooling system which results in temperature exceedances within individual battery cells. This is a constant concern because charging and discharging cycles generate significant heat; like any mechanical system, BESS cooling equipment is susceptible to operational "glitches" and failure. When this happens, thermal runaway ensues.

Another cause of thermal runaway is installation errors at the BESS facility; many types of installation mishaps can trigger thermal runaway. For example, mishandling can damage a single battery cell in a manner that compromises the separator barrier; this

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[1] *What Causes Thermal Runaway*? Underwriter Laboratories Research Institutes. Accessed February 17, 2026. https://ul.org/research-updates/what-causes-thermal-runaway/

[2] *BESS QUALITY RISKS: Summary of the Most Common Battery Energy Storage System Defects*. February, 2024. https://info.cea3.com/hubfs/CEA%20BESS%20Quality%20Risks%20Report.pdf.

will cause a short circuit and thermal runaway will initiate. And, because BESS containers are always shipped and installed in a charged state, thermal runaway can occur even during shipping and installation; this is why several freeways in California have been closed after transportation mishaps involving LFP and NMC BESS containers. Other types of installation errors can also cause thermal runaway. For example, the Australian BESS fire described above resulted from a liquid coolant leak that occurred during construction. Installation errors sometimes do not reveal themselves until after construction is complete and the system is online. This was the case in one of the first BESS fires at Moss Landing which occurred because numerous vent shields were improperly installed. One of the improperly installed vent shields dislodged an umbrella valve which caused significant quantities of water to pour onto the stacked battery cells; this shorted them out and thermal runaway was immediately initiated.

Given the numerous pathways for initiating thermal runaway and the high number of manufacturing deficiencies reported by CEA, it is surprising that there have not been *more* BESS explosions and fires. Nonetheless, more BESS fires will occur over time because manufacturing defects and installation errors will eventually assert themselves and because BESS units degrade as they age[3]; for instance, the separator barrier between the anode and cathode degrades with time and thus creates a progressively higher probability that a short circuit will occur and initiate thermal runaway.

MISCONCEPTIONS ABOUT BESS FACILITIES AND PRAIRIE SONG.
There are many misconceptions regarding BESS facilities in general and the Prairie Song project in particular.

The developer and the consultants hired by the developer have stated several times that the proposed location of the Prairie Song BESS is perfect. However, the higher probability of deflagration frequencies that is posed by the sheer size of the project, coupled with its configuration (stretching more than a mile and winding around Acton homes) and location in a windy area with limited water resources poses means that it is placed in the ***worst possible location.***

Energy interests and energy developers have perpetuated many myths about LFP BESS which have given the public and decisionmakers a false impression that LFP BESS are "safe". For example, at a public workshop sponsored by the Commission in 2024, a

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[3] "[B]atteries remain the primary cost component for BESSs. Due to a multitude of cell internal aging mechanisms, lithium-ion cells are subject to degradation, which manifests itself in capacity loss, cell resistance increase, as well as safety implications." *Aging aware operation of lithium-ion battery energy storage systems: A review*. Nov, 25, 2022. N. Collath, B. Tepe, S. Englberger, A. Jossen, H. Hesse. https://www.sciencedirect.com/science/article/pii/S2352152X2201622X

panel member representing the energy industry assured that LFP batteries "can be designed to be safe" and that "concerns about the thermal runaway and the intensity of fires" do not apply to LFP batteries"[4]. As the evidence provided above demonstrates, these statements are categorically false. At a presentation convened by a BESS developer on August 12, 2025, Acton residents and representatives of elected officials were assured that LFP BESS facilities are "safe"[5]. These assurances are meaningless. As explained above, LFP batteries are susceptible to thermal runaway and when it occurs, the resulting fires are *more intense* and *burn faster* than other lithium chemistries because they release more hydrogen gas and hydrocarbons. Contrary to what has been conveyed to the Commission, elected officials, and the public, *no lithium-based battery can be designed to eliminate the threat of thermal runaway*. This fact was affirmed in an analysis prepared in 2023 for the CPUC which explains that every component of a lithium BESS unit is "a potential **point of failure**—the risk of which can be minimized via quality control, testing, and ongoing monitoring and maintenance but cannot be entirely eliminated"[6].

Another myth perpetuated by energy developers and energy interests is that the public safety risk posed by a BESS facility is independent of the size of the facility. However, thermal runaway is a phenomenon that initiates at the battery cell level, so the more battery cells that are present, the more likely a thermal runaway event will be initiated. This, coupled with the multitudinous mechanisms for BESS failure (due to defects, installation errors, mechanical failures, etc.), increases the likelihood of thermal runaway. If one assumes these failures are randomly distributed, then it is axiomatic that, as the total number of BESS units increase in a given area, the number of BESS failures will also increase in the area; this increases the probability of ignition. This myth also mistakenly presumes that any given BESS facility will only ever experience a "single unit failure" when in fact BESS facilities can experience successive "single unit failure" events over time where each "single unit failure" has the potential to result in a significant public safety event (such as the four BESS fires that required multiple fire department responses at the Sanborn BESS facility in 2024). In other words, what drives the risks posed by a BESS is not just that a "single unit" will fail and cause a

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[4] Scott Murtishaw from the California Energy Storage Alliance (a consortium of energy developers) made these remarks as a panelist at a BESS Safety workshop convened by the Commission on Feb. 23, 2024. Mr. Murtishaw stated LFP batteries "*can be designed to be safe…. as the industry is moving towards more Lithium Iron Phosphate, a lot of the concerns about the thermal runaway and the intensity of those fires actually apply to NMC and not to Lithium Ion Phosphate*" [Timestamp 1:11:07]. The recording is here: https://efiling.energy.ca.gov/GetDocument.aspx?tn=254710&DocumentContentId=903

[5] This assurance was provided by representatives of Fullmark Energy, an energy developer that is advancing plans to construct the "Maathai" BESS in East Acton.

[6] CPUC Energy Storage Procurement Study: Safety Best Practices. Attachment F. Found here: https://lumenenergystrategy.com/uploads/1/3/6/3/136375767/2023-05-31_lumen_energy-storage-procurement-study-report-attf-final.pdf at F-6

public safety response; BESS risks are also driven by the fact that "single unit" failures can occur at the same facility successively over time. And, because the probability of a "single unit failure" increases as the number of BESS units increase, the frequency with which these "single unit failures" will occur is much higher at large BESS facilities and in areas where multiple BESS facilities are located. Therefore, projects like the Prairie Song that have thousands of BESS containers will experience far more BESS fires than a small 10 MW facility with only two BESS containers; these circumstances make it even more risky to approve the project Acton in Acton.

Another misconception is that BESS facilities are safe because they are constructed with "layered" protection systems using three basic mechanisms: 1) a BMS; 2) a Detection System; and 3) a Fire suppression system. However, these "layered" mechanisms are themselves not "failsafe" and they *do not* render BESS "safe":

The BMS System: coordinates and integrates battery operations and is supposed to ensure that the many battery cells in a BESS unit never overheat, overcharge, or overdischarge. However, BMS are not infallible and, like the batteries themselves, can have manufacturing defects, installation errors, and operational "glitches". Given that thermal runaway can be initiated when just *one* of the battery cells in a BESS becomes overcharged (which, as described above, is a particular concern for LFP BESS), the fallibility of BMSs render this "protection layer" to be susceptible to failure.

The Detection System: involves detecting the presence of combustible gas or smoke; when this occurs, the operator can halt the BESS charging/discharging process, activate alarms, and open vents. However, "Detection" does not "warn" of a possible thermal runaway event; rather is confirms that a thermal runaway is already initiated. In fact, the combustible gas that these systems detect is the vaporized electrolyte solution which battery cells release *after* thermal runaway is initiated. Thus, "Detection" does not prevent or avoid thermal runaway; rather, it notifies an operator that thermal runaway is initiated.

The Fire Suppression System: involves "putting out" a BESS fire. However, BESS fires involve self-reactive electrochemical energy and they can sustain themselves without oxygen; therefore, they persist and reignite in any cell where the thermal runaway initiation temperature is exceeded *regardless of the suppression material*. That is why emergency responders remain at a BESS fire for days and even weeks with water hoses "at the ready". For instance, it took firefighters nearly 17 days to "clear the scene" at the Otay Mesa BESS fire that ignited on May 15, 2024 and which persistently reignited.

The Layered System: The "layers" touted by energy developers (BMS, Detection, and Fire Suppression) are functionally distinct without significant overlap. Therefore, none of the layers are redundant which means that each individual "layer" must continuously work perfectly at all times (which is unlikely because mechanical systems are not immune to malfunction).

Another myth is that thermal runaway only happens during charging and discharging, and that, because the "battery management system" controls charging and discharging, it will stop either process when the onset of thermal runaway is detected. However, it is incorrect to state that thermal runaway only happens during charging and discharging. In fact, lithium batteries that are not connected to anything are known to deflagrate; for example, a number of oceangoing container ships have sunk because a lithium battery pack that was being transported spontaneously ignited.

Another misconception is that BESS fires do not release toxic gases and are treated like any other fire scenario. In fact, the Prairie Song developer actually made this claim in the presentation that was given at the Scoping meeting! This statement was also made by a consultant working on behalf of an energy developer who told the Los Angeles County Board of Supervisors that BESS fires are "similar to other fire scenarios" and "can be treated with the same precautions as something like a sofa, mattress, or office fire"[7]. To support this claim, the consultant pointed to a study conducted in 2017 that measured toxic emissions from the ignition of small individual battery cells. However, the consultant deliberately misrepresented the report which actually states that "a smoldering Li-ion battery" can be "treated with the same precautions as something like a sofa, mattress, or office fire in terms of toxicity". The "sofa fire" equivalency drawn by the report pertained to a *single* lithium battery cell, not an entire BESS unit which has hundreds of thousands of battery cells[8]. Furthermore, the consultant failed to mention that the report showed peak toxic emission concentrations from lithium battery cells were 10 times higher[9] which means that lithium battery fires are substantially more deadly *because the danger posed by toxic gas emissions is driven by concentration*.

Another example of a consultant trivializing the risks posed by BESS fires occurred during a recent workshop hosted by the County of Los Angeles[10] where the consultant

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[7] See page 15 of a 19 page "memo" written on behalf of Hecate Grid LLC (now known as Fullmark Energy) and dated August 14, 2024 which is appended to a letter to the Board of Supervisors dated October 8, 2024 and found here: https://file.lacounty.gov/SDSInter/bos/supdocs/197666.pdf.

[8] *Considerations for ESS Fire Safety* Consolidated Edison and NYSERDA Report No.: OAPUS301WIKO(PP151894), Rev. 4. February 9th, 2017. https://www.nyserda.ny.gov/-/media/Project/Nyserda/Files/Publications/Research/Energy-Storage/20170118-ConEd-NYSERDA-Battery-Testing-Report.pdf. Page 10.

[9] Id at Figure 4.

[10] The consultant was Mr. Robert Davidson who apparently manages "Davidson Code Concepts LLC" and provides consulting to energy interests. For example, in March of 2025, Mr. Davidson offered comments on BESS safety to the Texas State Senate on behalf of the "Advanced Power Alliance" and "Texas Solar+Storage Association" [https://poweralliance.org/wp-content/uploads/2025/03/CCG-SB1825-and-CV.pdf]. Advanced Power Alliance is a consortium of energy developers/interests

said that HF emissions are a "misnomer", that HF produced by BESS fires dissipate within yards of the BESS[11], and that "HF isn't the issue"[12]. It was pointed out by other attendees that air monitoring results from BESS fires are always unreliable because they occur long after the BESS fire is initiated. For example, EPA did not begin monitoring for HF at the Vistra BESS fire until January 18, 2025[13] even though the fire ignited on January 14, 2025. Even at this late date, HF was detected.

The abysmal monitoring practices that are typically implemented in response to BESS fires were particularly evident in the response to a 2024 BESS fire in the City of Escondido. According to the report[14], air quality monitoring did not even begin until hours after BESS deflagration initiated[15] so it provides no data for the most crucial portion of the event. Additionally, measured HCN concentrations were nearly half of the 4.7 part per million "never to be exceeded" level set by the National Institute of Occupational Health ("NIOSH")[16]; this means that toxic compounds were present at worrying levels. Perhaps the most significant deficiency is that no air monitoring for Hydrogen Fluoride (HF) was even conducted; instead, the HAZMAT team used "Fluoride Paper"[17]. However, "Fluoride Paper" is incapable of detecting fluoride at the NIOSH toxicity level of 6 parts per million[18] (5 mg/m^3); in fact, manufacturer specifications indicate that "Fluoride Paper" cannot even detect fluoride until it reaches a concentration of 20 mg/L[19] (or 20,000 mg/m^3). This means the HF measuring methodology used for the SDGE BESS deflagration event is so insensitive that it can only detect HF when HF concentrations are 4,000 times higher than the NIOSH toxicity limit! Said another way, if HF had been present in concentrations that were sufficiently high to be detected by the "Fluoride paper", then every living thing near the sample site would already be long dead.

(https://poweralliance.org/); Texas Solar+Storage Association is a trade association that promotes the deployment of energy storage and solar resources in Texas (https://txsolarstorage.org).

[11] "Battery Energy Storage Systems in LA County" workshop convened June 17, 2025. Timestamp 1:51:00. https://planning.lacounty.gov/wp-content/uploads/2025/06/BESS_Meeting_Recording.mp4 .

[12] Id. [Time stamp 1:53:15].

[13] https://www.readymontereycounty.org/emergency/2025-moss-landing-vistra-power-plant-fire/testing/air

[14] https://www.escondido.gov/DocumentCenter/View/6716/SDGE-Battery-Fire-Air-Quality-Report-PDF?bidId=

[15] According to the last page of the report, BESS deflagration began before noon on September 5, but page 2 reports that monitoring did not begin until 2:30 PM.

[16] Page 4 identifies exposure limits; page 5 provides monitoring results. Note: HCN levels were 2 ppm.

[17] The last page states "Fluoride reactive test strips" were used.

[18] https://www.osha.gov/chemicaldata/622

[19] https://ctlscientificsupply.com/flyers/hazmat.pdf

ATTACHMENT 10

STUDY OF LOW FREQUENCY NOISE EFFECTS.

Low Frequency Noise and Annoyance

H.G. Leventhall

Noise and Vibration Consultant, Ashtead, Surrey, UK

Low frequency noise, the frequency range from about 10Hz to 200Hz, has been recognised as a special environmental noise problem, particularly to sensitive people in their homes. Conventional methods of assessing annoyance, typically based on A-weighted equivalent level, are inadequate for low frequency noise and lead to incorrect decisions by regulatory authorities.

There have been a large number of laboratory measurements of annoyance by low frequency noise, each with different spectra and levels, making comparisons difficult, but the main conclusions are that annoyance of low frequencies increases rapidly with level. Additionally the A-weighted level underestimates the effects of low frequency noises.

There is a possibility of learned aversion to low frequency noise, leading to annoyance and stress which may receive unsympathetic treatment from regulatory authorities. In particular, problems of the Hum often remain unresolved.

An approximate estimate is that about 2.5% of the population may have a low frequency threshold which is at least 12dB more sensitive than the average threshold, corresponding to nearly 1,000,000 persons in the 50-59 year old age group in the EU-15 countries. This is the group which generates many complaints.

Low frequency noise specific criteria have been introduced in some countries, but do not deal adequately with fluctuations. Validation of the criteria has been for a limited range of noises and subjects.

Keywords: Noise, low frequency noise, annoyance, subjective efforts, disturbance

Introduction

Low frequency noise, considered as the frequency range from about 10Hz to 200Hz, causes extreme distress to a number of people who are sensitive to its effects. The sensitivity may be a result of heightened sensory response, within the whole or part of the auditory range, or may be acquired. Onset of low frequency noise annoyance tends to occur in middle age. The noise levels are often low, in the region of a subject's hearing threshold, where there are large differences between individuals. The problem arises both in homes and in offices, or similar, premises. Whilst noise sources causing annoyance in the home may be unknown, in offices they are often fans or pumps in the building services. Similar plant, in those apartment blocks which have central services, may be the source of the noise in these premises, but a core of low frequency noise problems remain, of unknown origin, which continue to cause considerable annoyance. Low frequency noise problems also occur in industry, but generally at levels well above threshold, presenting a different noise problem to those in homes and offices.

Attempts to assess low frequency noise by conventional wide-band noise methods often fail, so illustrating the inadequacy of these methods for low frequencies. In particular, the regulatory dominance of A-weighted levels, leads to dismissal of valid problems of low frequency noise, so compounding the difficulties of some complainants

The World Health Organization recognizes the special place of low frequency noise as an environmental problem. Its publication on

Community Noise (Berglund et al., 2000) makes a number of references to low frequency noise, some of which are as follows

"It should be noted that low frequency noise, for example, from ventilation systems can disturb rest and sleep even at low sound levels"

"For noise with a large proportion of low frequency sounds a still lower guideline (than 30dBA) *is recommended"*

"When prominent low frequency components are present, noise measures based on A-weighting are inappropriate"

"Since A-weighting underestimates the sound pressure level of noise with low frequency components, a better assessment of health effects would be to use C-weighting"

"It should be noted that a large proportion of low frequency components in a noise may increase considerably the adverse effects on health"

"The evidence on low frequency noise is sufficiently strong to warrant immediate concern"

Annoyance

The meaning of annoyance

Annoyance has roots in a complex of responses, which are moderated by personal and social characteristics of the complainant. (Belojevic and Jokovljevic, 2001; Benton and Leventhall, 1982; Fields, 1993; Grime, 2000; Guski, 1999; Guski et al., 1999; Kalveram, 2000; Kalveram et al., 1999; Stallen, 1999).

For example, Guski (1999) proposes that noise annoyance is partly due to acoustic factors and partly due to personal and social moderating variables as follows:

Personal Moderators: Sensitivity to noise. Anxiety about the source. Personal evaluation of the source. Coping capacity with respect to noise.
Social Moderators: Evaluation of the source. Suspicion of those who control the source. History of noise exposure. Expectations

Noise annoyance in the home is considered as leading to a long-term negative evaluation of living conditions, dependent on past disturbances and current attitudes and expectations. Annoyance brings feelings of disturbance, aggravation, dissatisfaction, concern, bother, displeasure, harassment, irritation, nuisance, vexation, exasperation, discomfort, uneasiness, distress, hate etc, some of which combine to produce the adverse reaction.

Figure 1, modified from Guski (1999) in order to emphasise the central nature of the personal factors, summarises the interactions. The interpretation of Figure 1 is as follows. The noise load causes activity interference (e.g. to communication, recreation, sleep), together with vegetative reactions (e.g. blood pressure changes, defensive reactions). Interference with activity develops into annoyance and disturbance. Prolonged vegetative reactions may lead to effects on health. The personal factors interact with the outer boxes of Figure 1, moderating the complainant's complex of responses. The social factors moderate how the complainant interacts with external authorities in attempting to deal with the annoyance. Social factors may also interact with health effects, as some social classes may more readily seek medical assistance. The personal and social moderating factors are so variable that Grime (2000) questions the feasibility of developing a national noise policy.

Annoyance and the "meaning" of noise

Kalveram (2000) points out that much psychoacoustical noise research has limitations, because it is based upon the correlation between annoyance ratings and physical measurements of sound energy, often equivalent level, leading to noise dose. But equivalent level, A-weighted or linear, is only a part of the total process. Noise level and noise dose approaches neglect the "meaning" of a noise and are contrary to the interactive model in Figure 1. The noise level / noise dose assessment reduces Figure 1 to Figure

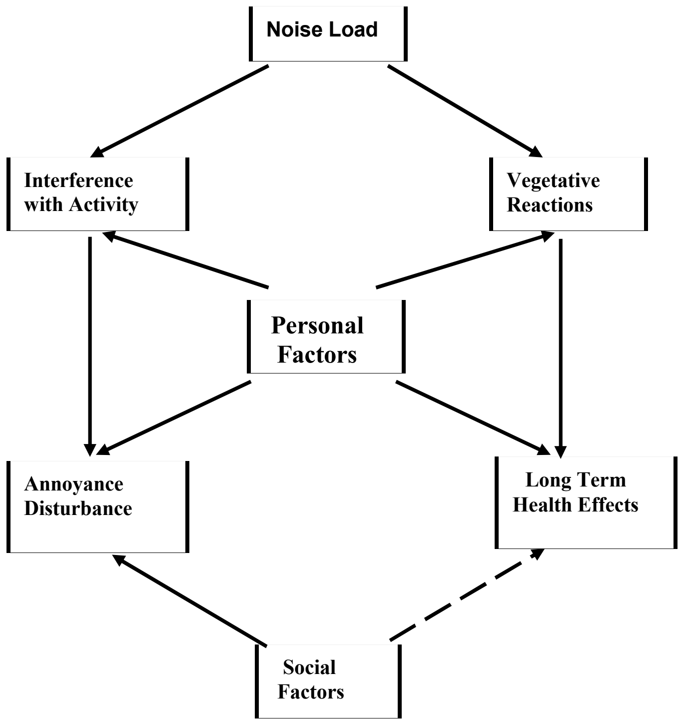

Figure 1. Factors moderating noise annoyance

2, in which the personal factors are constrained to those of the average person, so that only a limited number of subjects are protected by criteria which are developed from the assessment.

Kalveram proposes an "ecological" approach, which emphasises the psychological functions of sounds. Annoyance originates from acoustical signals which are not compatible with, or which disturb, these psychological functions. In particular, disturbance of current activities is a primary effect of noise exposure, producing a potential loss of fitness in the subject with respect to those behaviour patterns which permit coping with changes in the environment. Presence of a harmful sensory variable in the environment leads to actions which interrupt current behaviour, in an attempt by the subject to reduce the sensory input. This tests the coping capacity of the individual.

Those who have experienced long-term exposure to low frequency noise may recognise this within themselves. However, a few persons are known to have modified their responses to low frequency noise, thereby removing it from the category of a challenge and threat.

Most field work on noise annoyance has been where there is a known source, for example air or road transport. The particular circumstances of some low frequency noise problems, where the noise source is not known, adds an additional element to annoyance. Those affected suffer extreme frustration and may find it necessary to assume a source, thus enabling themselves to cope through provision of a focus for anger and resentment. Assumed sources have included neighbours, gas pipelines, radio transmissions and defence establishments.

Annoyance Measurements

Annoyance measurements are generally of the type described by Kalveram (2000), an attempt to relate annoyance ratings directly to measured noise levels. As described above, these measurements are limited in their results, since they deal with only part of the annoyance complex.

Laboratory determinations

There have been a large number of laboratory determinations of annoyance of low frequency sounds, mainly measurements using either 'normal' or 'sensitive' subjects. Stimuli have included tones, bands of noise or specially

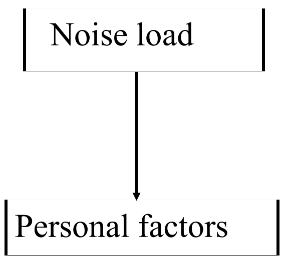

Figure 2. Noise dose interaction

developed spectra. There is, of course, a wide range of possible stimuli, which experimenters have chosen according to their experience of what is required (Adam, 1999; Andresen and Møller, 1984; Broner and Leventhall, 1978; Broner and Leventhall, 1984; Broner and Leventhall, 1985; Goldstein, 1994; Goldstein and Kjellberg, 1985; Inukai et al., 2000; Kjellberg and Goldstein, 1985; Kjellberg et al., 1984; Møller, 1987; Nakamura and Inukai, 1998; Persson and Bjorkman, 1988; Persson-Waye, 1985; Poulsen, 2002; Poulsen and Mortensen, 2002). Some of the laboratory studies have used recordings of real noises as stimuli, whilst others have worked with recordings of the actual noises as experienced by subjects in their own work places or homes. (Holmberg et al., 1993; Landström et al., 1994; Manley et al., 2002; Mirowska, 1998; Mortensen and Poulsen, 2001; Poulsen and Mortensen, 2002; Tesarz et al., 1997; Vasudevan and Gordon, 1977; Vasudevan and Leventhall, 1982).

Most determinations have been aimed at relating the A-weighted level, or some other derivative of the spectrum of the low frequency noise, to its annoyance. Whilst they are adequate studies, and have shown some general factors in low frequency noise annoyance, they are limited in that their results apply only to the particular noises investigated, often with a small number of subjects. It is unlikely that continued studies of this kind will result in step changes in our understanding of low frequency noise annoyance. However, Poulsen and Mortensen (2002) are an advance on previous work, as they compare subjective assessments with criteria, which have been developed in some European countries, specifically for assessment of low frequency noise.

Experimental methods

The responses required from subjects vary with experimental method. In laboratory investigations, subjects may be asked to ‘“imagine” themselves relaxing in their homes in the evening and to rate annoyance by, for example, choice on a semantic scale ranging from ‘Not Annoying’ to ‘Extremely Annoying’. Other methods include marking the level of annoyance on an unnumbered linear scale at a point between ‘Not at all annoying’ and ‘Very annoying’, or assigning a number to a reference noise and appropriate numbers to other noises in order to estimate their magnitudes. These psychological techniques are well established, but need care in their performance, as they are sensitive to experimental factors.

Equal annoyance contours

The main results of this work are as follows. Møller (1987) investigated contours of equal annoyance for pure tones in the frequency range 4Hz to 31.5Hz. The annoyance contours are influenced by the narrowing of the range of equal loudness contours at low frequencies. Møller’s results are shown in Figure 3. The vertical scale is the annoyance rating in terms of the distance marked for the tone along a 150mm linear scale. The lowest frequencies must be at a higher level than other frequencies in order to become audible but, once they are audible, their annoyance increases rapidly. For example, the scale rating range at 4Hz is about 10dB between extremes of annoyance. 8Hz and 16Hz have a 20dB range, whilst 31.5Hz has nearly 40dB range. The 1000Hz comparison, which is for an octave band of noise, has a range of nearly 60dB. These findings are important, as they confirm that the hearing contours are reflected in annoyance, although loudness and annoyance are not necessarily the same. Figure 3 gives averages for 18 subjects with normal hearing.

Individual annoyance functions

Broner and Leventhall (1978) measured individual annoyance functions for 20 subjects using ten low frequency noise stimuli. The

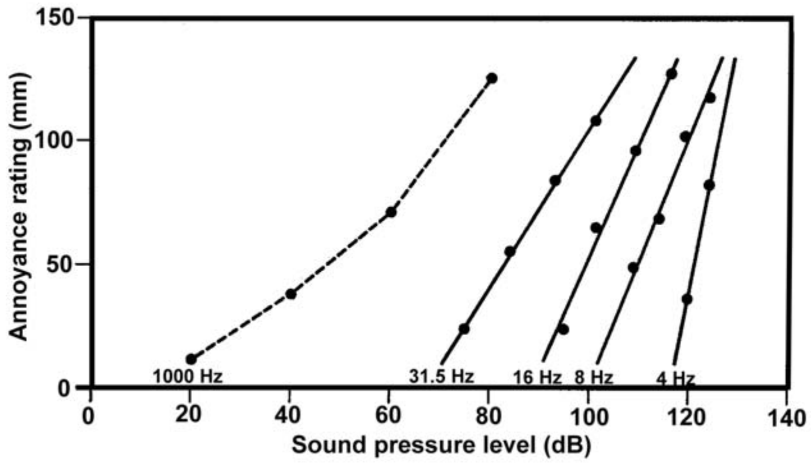

Figure 3. Annoyance rating, showing rapid growth at low frequencies

psychophysical function was assumed to be a simple power function

$$\psi = k\varepsilon^{\beta}$$

Where ψ represents the estimation of psychological magnitude, ε is the stimulus intensity and β a subject-specific exponent. It was shown that there was a wide range of individual exponents, β, from a low of 0.045 to a high of 0.4 and three groupings of individual differences were identified. Previous work at higher frequencies had also shown individual loudness functions (Barbenza et al., 1970) and had posed the question of whether one set of regulations should be applied to all people (Bryan and Tempest, 1973).

Annoyance and the dBA

A comparison of a band of noise peaking at 250Hz with a band peaking at 100Hz, whilst both were adjusted to the same A-weighted level, showed that the annoyance from the low frequency noise was greater than that from the higher frequency noise at the same A-weighted level (Persson et al., 1985) . This work was subsequently extended (Persson and Bjorkman, 1988; Persson et al., 1990) using a wider range of noises, for example, peaking at 80Hz, 250Hz. 500Hz and 1000Hz, leading to the following conclusions:

* There is a large variability between subjects.
*The dBA underestimates annoyance for frequencies below about 200Hz.

For broadband low frequency noise, the underestimate was found to be 3dB for levels around 65dB(Linear) and 6dB for levels around 70dB(Linear). Similar results had been obtained in earlier work (Kjellberg et al., 1984). Two broadband noises were investigated, in which one was dominated by energy in the 15-50Hz range. Twenty subjects compared the two noises within the dynamic range 49-86dBA. At equal A-weighted levels, the noise dominated by the low frequency component was perceived as 4-7dB louder and 5-8dB more annoying.

The energy input to the subjects was, of course, greater for the low frequency noises due to the attenuating effect of A-weighting, and it might be expected that there would be a greater effect, perhaps suggesting that loudness, assumed related to the A -weighting, differs from annoyance at low frequencies.

Unpleasantness

The "unpleasantness" of low frequency noise has also been estimated (Inukai et al., 2000; Nakamura and Inukai, 1998). Nakamura and Inukai used a stimulus sound of a pure tone in 20 conditions from 3Hz to 40Hz and sound pressure levels from 70dB to125dB, with evaluation by 17 subjects. There were four main subjective factors in response to low frequency noise: auditory perception, pressure on the eardrum, perception through vibration of the chest and more general feeling of vibration. Analysis of the responses showed that auditory perception was the controlling factor. That is, although high levels of low frequency noise may produce other sensations, the ear is the most sensitive receptor.

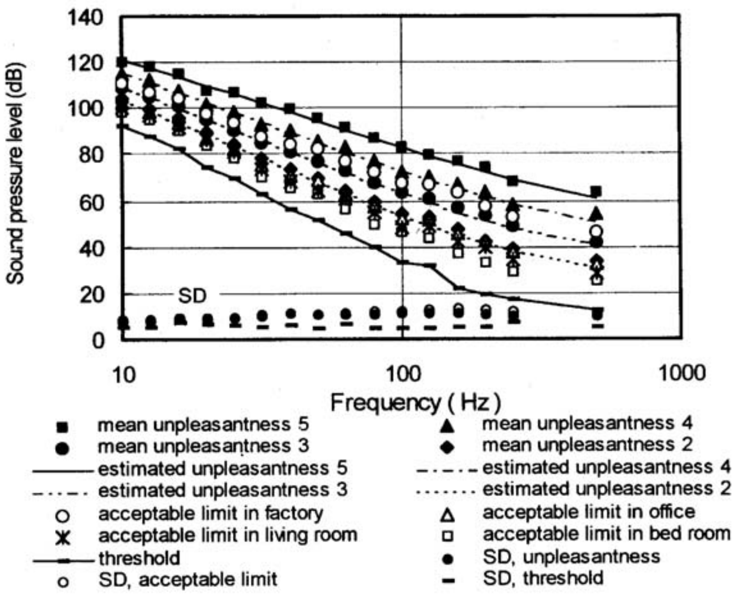

Figure 4. Equal unpleasantness contours and acceptable limits (Inukai)

Inukai et al (2000) determined "equal unpleasantness" contours for 39 subjects over a tone frequency range of 10Hz to 500 Hz. A verbal scale was used ranging through: *Not at all unpleasant (1) - somewhat unpleasant (2) – unpleasant(3) – quite unpleasant(4) – very unpleasant(5)*. Subjects in a test chamber were asked to assume different home and work situations and adjust the level of a tone to match a level on the scale, as requested by the experimenter. For example if instructed to match to level 4 (*quite unpleasant*), subjects would adjust the tone until they judged that this level was reached. Results are shown in Figure 4. The numbers 1,2,3,4,5 refer to the unpleasantness level. All levels of unpleasantness are approximately linear with a negative slope of 5 - 6dB per octave. The acceptable limits for different locations are all above the hearing threshold in this laboratory setting. For example, the self-adjusted acceptable limit in an assumed bedroom is more than 10dB above threshold, but this might not be replicated for long term exposure at night in a real bedroom.

Spectrum balance

The work by Inukai et al (2000) was for single tones. Spectrum balance has also been considered a factor in noise annoyance of a wideband spectrum. Correlation of a number of complaints with the corresponding spectra (Bryan, 1976) led to the conclusion that, for spectra which averaged as shown in Figure 5, a fall off above 32Hz of 5.7dB/octave was acceptable, whilst a fall off from 63Hz at 7.9 dB/octave was unacceptable. Work on acceptable spectra of air conditioning noise in offices led to similar conclusions (Blazier, 1981). Blazier found that, on average, acceptable office environments had a fall off of 5dB/octave. An excess of low frequency noise led to rumble, an excess of mid frequency noise led to roar, whilst an excess of high frequency noise led to hiss. Later work (Blazier, 1997) developed a "Quality Assessment Index" for an HVAC noise through the balance of low, mid and high frequencies.

(dBC – dBA) weighting.

The difference between C- and A-weightings has also been considered as a predictor of annoyance (Broner, 1979; Broner and Leventhall, 1983; Kjellberg et al., 1997), as this difference is an indication of the amount of low frequency energy in the noise. If the difference is greater than 20dB, there is the potential for a low frequency noise problem. Kjellberg et al used existing noise in work places (offices, laboratories, industry etc) with 508 subjects. Three sub- groups were obtained with a maximum difference in low and high frequency exposure. The conclusions on correlations of (dBC – dBA) difference and annoyance were that the difference is of limited value, but, when the difference exceeds 15dB, an addition of 6dB to the A-weighted level is a simple rating procedure. However, the difference breaks down

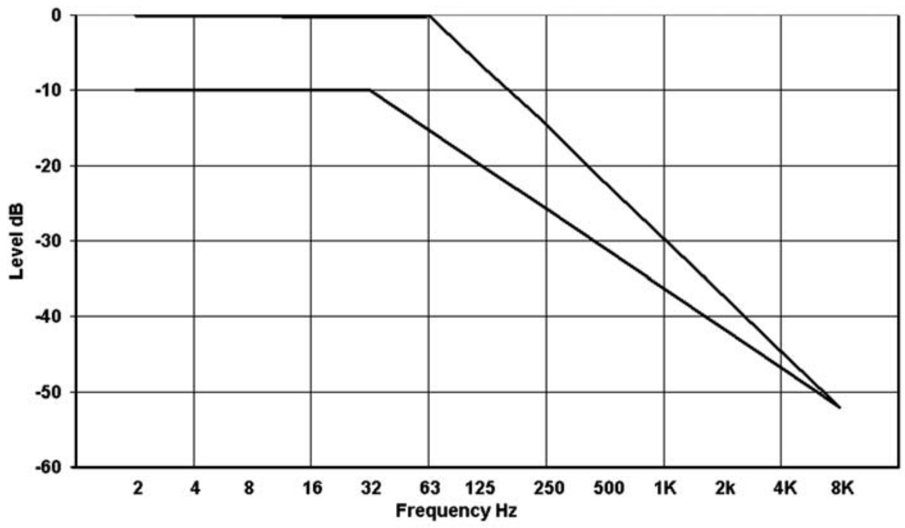

Figure 5. Acceptable and unacceptable spectrum slopes

when the levels are low, since the low frequencies may then be below threshold. The (dBC – dBA) difference cannot be used as an annoyance predictor, but is a simple indicator of whether further investigations may be necessary.

Home and work environments

Other studies, have assessed low frequency noise in real or assumed work environments or in the home (Bryan, 1976; Cocchi et al., 1992; Holmberg et al., 1997; Holmberg et al., 1993; Holmberg et al., 1996; Landström et al., 1993; Landström et al., 1994; Lundin and Ahman, 1998; Mirowska, 1998; Vasudevan and Gordon, 1977; Vasudevan and Leventhall, 1982).

Homlberg et al (1996 and 1997) assessed noise in real environments. The 1996 paper compared responses of about 240 subjects with the noise measures which might be available on a sound level meter i.e. dBLIN, dBA, dBB, dBC and dBD and the difference (dBC-dBA). Additionally, Zwicker loudness (ISO532, 1975) and Low Frequency Noise Rating (LFNR) (Broner and Leventhall, 1983) were calculated. There was poor correlation between the sound level meter weightings and annoyance. Similarly, the loudness in sones and the difference (dBC – dBA) did not correlate well.

The LFNR did separate out annoying and not annoying noises, but no more effectively than the (dBC – dBA).

Level variations

Holmberg et al (1997) investigated noise in workplaces, using the (dBC – dBA) difference as an indicator. Low frequency noise exposure was found in a group of 35 out of a total of 337 persons. Measurements of temporal variation of the levels of low frequency noise at the workplaces, averaged over 0.5, 1.0 or 2.0 seconds, was correlated with subjective annoyance. Significant correlation was found between the irregularity of the noise levels and annoyance.

This work represents an advance, in that it shows the importance of fluctuations in noise level. A limitation of much work on assessment of low frequency noise has been that long term averaged measurements were used and, consequently, information on fluctuations was lost, although complaints of low frequency noise often refer to its throbbing or pulsing nature. Broner and Leventhall(1983) had noted the importance of fluctuations and suggested a fluctuation penalty of 3dB in the Low Frequency Noise Rating Assessment. The importance of fluctuations has also been assessed in laboratory experiments (Bradley, 1994). Subjects listened first to steady wideband noises which peaked at 31.5Hz and adjusted the overall level of these to be equally annoying to a reference spectrum which fell at 5dB/octave. It was found that the more prominent the low frequency noise, the greater the reduction in level required for equality of annoyance with the reference spectrum. The test spectra were now amplitude modulated, in the low frequency region only, at modulation frequencies of 0.25, 0.5, 1.0, 2.0 and 4.0Hz and depths of 10dB and 17dB. Subjects again adjusted the level of the noises to produce equal annoyance with the unmodulated reference noise. The reductions varied with modulation frequency and modulation depth. An example is that, for the highest modulation depth at 2.0Hz modulation frequency, the level was reduced by 12.9dB averaged over the subjects. This work confirms the importance of fluctuations as a contributor to annoyance, and the consequent limitation of those assessment methods which do not include fluctuations .

Field investigations

Vasudevan and Gordon (1977) carried out field measurements and laboratory studies of persons who complained of low frequency noise in their homes. A number of common factors were shown:

* The problems arose in quiet rural or suburban environments
* The noise was often close to inaudibility and heard by a minority of people
* The noise was typically audible indoors and not outdoors
* The noise was more audible at night than day
* The noise had a throb or rumble characteristic
* The main complaints came from the 55-70 years age group
* The complainants had normal hearing.
* Medical examination excluded tinnitus.

These are now recognised as classic descriptors of low frequency noise problems.

Further work in the laboratory showed that gradually falling spectra, as measured in the field and simulated in the laboratory, possessed a rumble characteristic. Figure 6 compares a measured noise on the left with a simulated noise on the right. Both fell at 7 – 8 dB/octave and had similar rumble characteristics. It is also known that a rapidly falling spectrum, such as one which follows the curve of the NR or NC ratings has an unpleasant quality. This was one reason for the development of the PNC rating as an improvement of the NC rating (Beranek et al., 1971). Further work (Vasudevan and Leventhall, 1982), confirmed that levels close to threshold caused annoyance, which increased if the noise also fluctuated. This work included spectra with tonal peaks and emphasised that the nature (quality) of the noise was important. Fluctuating noises are more annoying than predicted by their average sound levels.

Recent work on annoyance to people in their homes has been by Mirowska (1998) and Lundin and Ahman (1998). Both these papers considered annoyance due to plant or appliances, installed in, or adjacent to, living accommodation. Mirowska found problems from machinery, including transformers in electricity substations, ventilation fans, refrigeration units and central heating pumps. Lundin and Ahman investigated a husband and wife who experienced typical symptoms of aversion to low frequency noise. Refrigerators and freezers were suspected as the source of the offending noise which, in some parts of the building, was high at 50Hz. The time varying pattern of the noise, due to equipment cycling, was considered to add to its annoyance. However, there was no totally convincing link between effects on health and the noise.

Development of enhanced susceptibility.

It is known that different regions of the brain are responsible for different functions. The brain also possesses "plasticity", in the sense that parts within the same region may change their function. For example, extensive training in a frequency discrimination task in small mammals leads to improved discrimination ability and an expansion of the cortical area responsive to the frequencies which were used during training. (Schnupp and Kacelnick, 2002).

In humans, there is considerable plasticity in the brain during its early development, requiring appropriate stimuli for proper growth. Plastic adaptation is slower in the adult brain. Two examples of plastic adaptation are:

London taxi drivers are required to memorise many routes through London. Magnetic resonance imaging showed that the part of the brain associated with spatial navigation, the posterior hippocampus, enlarged at the expense

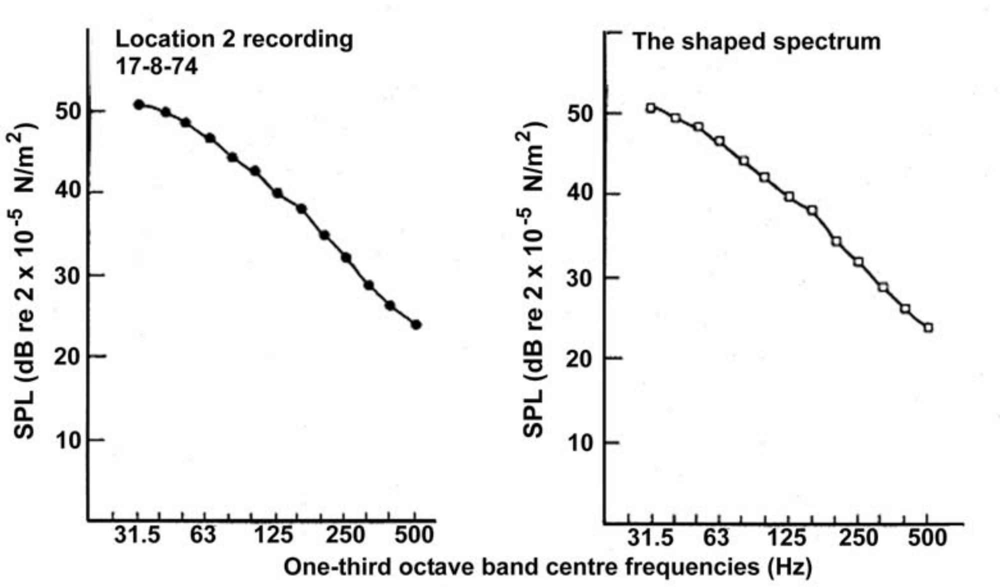

Figure 6. Measured spectrum (left) and simulated spectrum (right)

of neighbouring regions.(Maguire et al., 2000). There has been a similar finding for skilled musicians (Pantev et al., 1998). Cortical reorganisation was greater the younger the age at which music training began.

The significance of these findings for low frequency noise annoyance is:
There is clear evidence that the brain is able to adapt to stimuli.
If complainants spend a great deal of time listening to, and listening for, their particular noise, it is possible that they may develop enhanced susceptibility to this noise.

Enhanced susceptibility is therefore a potential factor in long-term low frequency noise annoyance.

Low frequency noise annoyance and stress
Stresses may be grouped into three broad types: cataclysmic stress, personal stress and background stress. Cataclysmic stress includes widespread and devastating physical events. Personal stress includes bereavements and other personal tragedies. Cataclysmic and personal stresses are evident occurrences, which are met with sympathy and support, whilst their impacts normally reduce with time. Background stresses are persistent events, which may become routine elements of our life. Constant low frequency noise has been classified as a background stressor (Benton, 1997; Benton and Leventhall, 1994). Whilst it is acceptable, under the effects of cataclysmic and personal stress, to withdraw from coping with normal daily demands, this is not permitted for low level background stresses. Inadequate reserves of coping ability then leads to the development of stress symptoms. In this way, chronic psychophysiological damage may result from long-term exposure to low-level low frequency noise.

Changes in behaviour also follow from long-term exposure to low frequency noise. Those exposed may adopt protective strategies, such as sleeping in their garage if the noise is less disturbing there. Or they may sleep elsewhere, returning to their own homes only during the day. Others tense into the noise and, over time, may undergo character changes, particularly in relation to social orientation, consistent with their failure to recruit support and agreement from the regulatory authority that they do have a genuine noise problem. Their families, and the investigating officer, may also become part of their problem. The claim that their “lives have been ruined” by the noise is not an exaggeration, although their reaction to the noise might have been modifiable at an earlier stage.

The HUM
Occurrence
Hum is the name given to a low frequency noise

which is causing persistent complaints, but often cannot be traced to a single, or any, source. If a source is located, the problem moves into the category of engineering noise control and is no longer “the Hum”, although there may be a long period between first complaint and final solution. The Hum is widespread, affecting scattered individuals, but periodically a Hum focus arises where there are multiple complaints within a town or area. There has been the Bristol Hum (England), Largs Hum (Scotland), Copenhagen Hum (Denmark), Vancouver Hum (Canada), Taos Hum (New Mexico USA), Kokomo Hum (Indiana USA) etc. A feature of these Hums is that they have been publicised in local and national press, so gathering a momentum which otherwise might not have occurred, possibly increasing the number of adverse reactions. Although the named Hums, such as Kokomo, have gained much attention, they should not be allowed to detract from the individuals who suffer on their own.

Hum character

The sound of the Hum differs between individuals. Even in the areas of multiple complaints, the description is not completely consistent, although this may be because people use different words to describe the same property of a noise. Publicity tends to pull the descriptions together. The general descriptors of the sound of the Hum include: a steady hum, a throb, a low speed diesel engine, rumble and pulsing. A higher pitch, such as a hiss, is sometimes attributed. The effects of the Hum may include pressure or pain in the ear or head, body vibration or pain, loss of concentration, nausea and sleep disturbance. These general descriptions and effects occur internationally, with close similarity.

Unsympathetic handling of the complaint leads to a build-up of stress, which exacerbates the problems. Hum sufferers tend to be middle aged and elderly, with a majority of women. They may have a low tolerance level and be prone to negative reactions. The knowledge that complaints are being taken seriously by the authorities helps to reduce personal tensions, by easing the additional stresses consequent upon not being believed. This is particularly so when, as is often the case, only one person in a family is sensitive to the noise. Whilst some Hum sufferers may have tinnitus, they will, of course, also be troubled by intruding noise at a different frequency from their tinnitus. Tinnitus should not be used as a reason to reject a complaint of low frequency noise annoyance.

Psychological aspects of the Hum

Psychosocial factors affect the physiological impact of noise (Hatfield et al., 2001). Adverse physiological consequences may be mediated by psychological factors related to the noise exposure. It is plausible that excessive noise exposure promotes negative psychological reactions, leading to adverse physiological effects, as was shown by Hatfield et al.(2001). Therefore, psychological factors must be addressed to help ameliorate the annoyance of low frequency noise.

Some Hum sufferers have achieved this for themselves, saying that they have “learnt to live with the Hum” so that it no longer worries them. Others are “cured” by prescription of relaxant drugs. For a few, the Hum goes away after a time. Some escape the Hum by moving house. One long term sufferer, and leading campaigner for official help with low frequency noise problems, decided that it was time to leave the low frequency forest of chaotic emotions and now has no problem, remaining detached from low frequency noise and of the opinion that to become involved with other sufferers heightens ones awareness of the noise. Some sufferers accept that the noises are not at a high level, but that their reactions are equivalent to those which might be expected from a high level of noise – “As soon as I hear the noise, something builds up inside me”. This is a similar response to that of hyperacusis sufferers, although more specialised in its triggers. A form of hyperacusis may be indicated.

Combined acoustical and psychological studies (Kitamura and Yamada, 2002) have explored involvement of the limbic system of the brain in annoyance responses[1]. The limbic system commands survival and emotional behaviours, which we cannot always control, although we may learn to do so.

The Hum remains a puzzling aspect of low frequency noise. No widespread Hum has been unequivocally traced to specific sources, although suspicion has pointed at industrial complexes, especially fans.

In the absence of known sources, Hum sufferers often search their neighbourhoods for a source, walking or driving around at night. It is important for them to find a target for their frustrations. Some general ones include their neighbours, the main gas pipelines, radio transmissions (particularly pulsed signals for navigation), defence establishments etc.

Auditory sensitivity

Special difficulties arise when, despite persistent annoyance, there is no "measurable" noise or, as might occur in urban areas, the noise levels at low frequencies are in the 40 - 50dB range, well below the average threshold (ISO:226, 1987). Van den Berg supports tinnitus as an explanation in these circumstances (van den Berg, 2001). With respect to audibility, the average ISO:226 threshold levels must be interpreted carefully. Van den Berg's choice of a limit criterion is the low frequency binaural hearing threshold level for 10% of the 50 – 59 year old population, which is 10-12 dB below their average hearing level (van den Berg and Passchier-Vermeer, 1999a). This may be too restrictive a cut off, since 10% of the age group has more sensitive hearing. For example, the population of the EU-15 countries is 379,000,000. There are differences between north and southern European countries, but approximately 10% of the population is in the 50 – 59 year age group. Thus, about 3,800,000 of the 50 – 59 year age group of the European population (10% of 10% of the total) will be more sensitive than the suggested cut-off for assessment of low frequency noise for this age group. A smaller number will have greater sensitivity. Yamada found one subject to be 15dB more sensitive than the average (Yamada, 1980), whilst recent work (Kitamura and Yamada, 2002), gives two standard deviations from the average threshold as about 12dB. However, the average threshold of the complainants in this work is somewhat higher than the ISO 226 threshold, as might be expected for older people. A range of two standard deviations covers 95% of people. Of the remaining 5%, half are more sensitive than two standard deviations from the average and half are less sensitive. In the EU-15 countries, 2.5% of the population is about 10,000,000 persons of whom around 1,000,000 are in the 50-59 year old age group, who might have very sensitive low frequency hearing and be prone to annoyance from sounds which are not heard by most people and which are difficult to measure. The unfortunate association of one of these people with a low level, low frequency noise leads to considerable distress for the person concerned. A "rule of thumb" may be to take 15 - 20dB below the ISO 226 threshold as the cut off for perception, but this may be a generous level, depending on the complainants' individual threshold at low frequencies.

The preceding deductions on numbers of persons are clearly approximate, but are sufficient to give an "engineering" indication of the extent of the problem.

Criteria for low frequency noise control.

A number of criteria have been developed for assessment of low frequency noise. (Broner and Leventhall, 1983; Challis and Challis, 1978; Inukai et al., 1990; Vercammen, 1989; Vercammen, 1992).

In recent years, some European countries have adopted national criteria for low frequency

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[1] The human brain has three layers representing its three stages of development. The primitive (reptilian) brain is connected with self preservation. The intermediate (old mammalian) brain is the brain of the inferior animals and related to emotions. This is the limbic system. The superior (new mammalian) brain is related to rational thought and intellectual tasks. The limbic system is activated by perceived threats.

Table 1. Test noises

No	Name	Description	Tones, characteristics
1	Traffic	Road traffic noise from a highway	None – broadband, continuous
2	Drop forge	Isolated blows from a drop forge transmitted through the ground	None – deep, impulsive sound
3	Gas turbine	Gas motor in a CHP plant	25 Hz, continuous
4	Fast ferry	High speed ferry; pulsating tonal noise	57 Hz, pass-by
5	Steel factory	Distant noise from a steel rolling plant	62 Hz, continuous
6	Generator	Generator	75 Hz, continuous
7	Cooling	Cooling compressor	(48 Hz, 95 Hz) 98 Hz, continuous
8	Discotheque	Music, transmitted through a building	None, fluctuating, loud drums

noise, including Sweden ((Socialstyrelsen-Sweden, 1996)), Denmark (Jakobsen, 2001) Netherlands ((N S G, 1999) Germany (DIN:45680, 1997) , Poland (Mirowska, 2002). Some of these methods assume a threshold curve for limitation of annoyance, based approximately on the ISO226 threshold, or a curve parallel to this threshold, but extended to frequencies below 20Hz.

The criteria have been compared under laboratory conditions for some specific noises (Poulsen, 2002; Poulsen and Mortensen, 2002). Noises used were eight recorded samples of different types as shown in Table 1.

The noises were judged by 18 otologically normal young listeners and by four older people (41-57 years) who had made complaints of annoyance by low frequency noise. Judgements were made under assumed listening circumstances of day, evening and night. The complaint group rated the noises to be more annoying than the other group did. Overall, the Danish method gave highest correlation between objective and subjective assessments, but only when a 5dB penalty for impulsive sounds was included.

Conclusions

Regulatory authorities must accept that annoyance by low frequency noise presents a real problem which is not addressed by the commonly used assessment methods. In particular, the A-weighted level is very inadequate, as are the NR and NC criterion curves. Assessment methods specific to low frequency noise are emerging, but a limitation of existing methods is that they do not give full assessment of fluctuations. It is possible that application of noise quality concepts, in particular fluctuation and roughness (Zwicker and Fastl, 1999), may be a way forward.

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Correspondence Address

H. G. Leventhall
Noise and Vibration Consultant, Ashtead, Surrey, KT21 1NL UK
E-mail: geoff@activenoise.co.uk

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ATTACHMENT 11

ADOPTED PLAN POLICIES, GOALS AND DEVELOPMENT OBJECTIVES THAT ARE CONTROVERTED BY THE BESS PROJECT.

CEQA compels compliance with General Plan goals, policies, and development objectives, and in weighing such compliance, Courts apply the fair argument standard when the goals, policies, and objectives were adopted to mitigate environmental effects [*Joshua Tree Downtown Business Alliance v. County of San Bernardino* 1 Cal.App.5th 677, *Pocket Protectors v. City Of Sacramento* (2004) 124 Cal.App.4th 903]. Accordingly, each inconsistency with an adopted County General Plan (General Plan) or Antelope Valley Area Plan (AV Area Plan) policy, goal, or objective that is posed by the proposed BESS constitutes a potentially significant environmental impact that must be addressed by the Commission when such policies, goals, and objectives were adopted for the purpose of mitigating environmental impacts. SORT has analyzed the policies, goals, and objectives enumerated in the AV Area Plan and the General Plan as well as the Environmental Impact Reports (EIRs) were certified for these Plans, and concluded that the proposed BESS creates more than 60 potentially significant environmental impacts because of the goals, policies, and objectives it intrinsically controverts.

AV Area Plan Policies That Were Adopted To Mitigate Environmental Impacts And Which Are Controverted By The Proposed BESS.

The EIR that was certified for the AV Area Plan clearly establishes that the policies, goals, and development objectives set forth therein were adopted for the purpose of avoiding environmental effects. Specifically, the EIR connects “land use impacts” to “land use incompatibilities” (page 5.10-1 of AV Plan EIR Section 5.10 provided in attached Document 1[1]) and establishes that the land use goals and policies adopted in the AV Area Plan “ensure land use compatibility throughout the Project Area” (Page 5.10-20 of attached Document 1). Together, these statements affirm that AV Area Plan goals and policies were adopted by the County to *ensure land use compatibility* and thereby *avoid direct environmental impacts*. More importantly, the EIR states “The following is a list of the goals and policies of the Proposed Project that would reduce potentially adverse effects concerning land use” and then lists virtually every goal and policy adopted by the AV Area Plan (pages 5.10-5 to 5.10-18 of attached Document 1). Additionally, the AV Area Plan Final EIR states that compliance with AV Area Plan goals and policies will ensure that environmental impacts (specifically, aesthetic impacts) are “less than significant” (pages 2-64, 2-48 of AV Plan Final EIR provided in attached Document 2). These EIR pages specifically establish that *virtually every goal and policy adopted by the AV Area Plan is intended to reduce environmental effects*; therefore, every AV Area Plan goal and policy that is controverted by the proposed BESS constitutes a significant environmental impact.

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[1] The Final EIR certified for the AV Area Plan consists of the Draft EIR, public comments received pursuant thereto, and responses prepared by the Lead Agency (see page 1-1 of Final EIR posted here: https://planning.lacounty.gov/wp-content/uploads/2022/10/Final-EIR.zip). The attached provides the relevant portions of the Draft EIR that comprise the Final EIR.

Additionally, the AV Area Plan establishes that the land uses designated therein mitigate noise, fire, air pollution, and other impacts (page I-6 of AV Area Plan - relevant excerpts are provided in attached Document 3); by extension, any uses that are not consistent with AV Area Plan land use designations are deemed to pose such impacts. Moreover, the AV Area Plan establishes that adopted goals and policies are implemented by the "Land Use Policy Map" through the "Rural Preservation Strategy"[2] and the "Community Specific Land Use Concepts"[3]; both the "Land Use Policy Map" and the "Community Specific Land Use Concepts" are founded on the "Land Use Legend" in Table L-1 which establishes the fundamental purpose of each land use category. Collectively, the "Land Use Policy Map", the "Rural Preservation Strategy", Table LU-1, and the "Community Specific Land Use Concepts" of the AV Area Plan implement the goals and policies, and as such, they were all adopted for the purpose of avoiding direct environmental impacts.

The 42 AV Area Plan goals, policies, and objectives that are directly controverted by the proposed BESS are identified in Table 1.

Table 1. AV Plan Policies that are Controverted by the BESS Project.

AV Area Plan Policy/Goal/Objective	Reason for Inconsistency
Policy LU 1.4: Ensure there are lands for commercial and industrial services throughout the unincorporated Antelope Valley sufficient to serve the daily needs of rural residents and to provide local employment opportunities.	The BESS is not consistent with the purpose of industrial uses in the Antelope Valley because it does not "provide local employment opportunities" or "serve the daily needs of rural residents".
Policy LU 3.2: Except within economic opportunity areas, limit the amount of potential development in Very High Fire Hazard Severity Zones, through appropriate land use designations with very low residential densities, as indicated in the Land Use Policy Map (Map 2.1).	Developer claims consistency simply because the BESS does not have residential uses. However, the BESS controverts this policy because it is a high density development in a Very High Fire Hazard Severity Zone (VHFHSZ) that poses a significant wildfire risk because it is prone to explosion and deflagration.
Policy LU 3.3: Except in economic opportunity areas, limit potential development in Flood Zones through appropriate land use designations with very low residential densities.	Developer claims consistency because the BESS is not a residential use. However, the non-residential development of a 500 kV transmission line) in a FEMA Flood Zone is facially inconsistent.

[2] The Rural Preservation Strategy creates a "pattern of rural town center areas, rural town areas, rural preserve areas, and economic opportunity areas" and together with the Land Use Policy Map, it lays out the "framework" for development. See pages LU-2 and LU-5 of attached Document 3.
[3] the "Community Specific Land Use Concepts" are established in AV Area Plan Chapter 7 and expressly describe how AV Area Plan Land Use goals and policies are implemented within each community. See Page COMM-1 of attached Document 3.

Policy LU 4.1: Direct the majority of the unincorporated Antelope Valley's future growth to the economic opportunity areas and areas that are served by existing or planned infrastructure, public facilities, and public water systems, as indicated in the Land Use designations shown on the Land Use Policy Map (Map 2.1) of this Area Plan.	Developer claims consistency because the BESS is remotely operated (which is irrelevant). However, the BESS entirely controverts this policy because it places a high density, high intensity industrial development in an area with ***no*** infrastructure, public facilities, or public water systems. Even worse, *the BESS site has no public water connections* and even if the BESS connected to the local municipal water system, the local system *does not have sufficient capacity to water needed to suppress the fires that will frequently erupt* from the massive BESS development. Everything about the BESS project substantially violates this policy and therefore substantially endangers the entire Community of Acton.
Policy LU 5.1: Ensure that development is consistent with the Sustainable Communities Strategy, an element of the Regional Transportation Plan developed by the Southern California Association of Governments.	The BESS controverts key elements of the current SCS[4], including "conservation of habitats that are prone to hazards exacerbated by climate change such as wildfires" (because it eliminates habitat in a VHFHSZ), "conservation of agricultural lands" (because it eliminates agricultural lands), and "support hazard [wildfire] planning in land use" (because it puts a dangerous, deflagration prone industrial development in a VHFHSZ at a site that has insufficient water resources to suppress the fires that will frequently erupt at the BESS site).
Policy LU 6.2: Ensure the Area Plan is flexible in adapting to new issues and opportunities without compromising rural character.	The BESS controverts this policy because it substantially compromises the rural character of Acton by blighting a designated rural, scenic, and agricultural area with an impermissible industrial development.
Policy COS 3.1: Discourage the use of chemical fertilizers, herbicides and pesticides in landscaping to reduce water pollution.	The BESS will substantially increase chemical usage in an existing natural area where such chemicals are not currently used.
Policy COS 3.4: Support preservation, restoration and strategic acquisition of open space to preserve natural streams, drainage channels, wetlands, and rivers, which are necessary for the healthy functioning of ecosystems.	Developer claims consistency because the BESS will be decommissioned.; however, the BESS controverts this policy by eliminating a massive open space and not preserving or restoring streams, drainage channels, wetlands, or rivers.

[4] 2024 SCAG Sustainable Communities Strategy; Page 119 [https://scag.ca.gov/sites/default/files/2024-05/23-2987-connect-socal-2024-final-ch-03-our-plan-040424.pdf].

Policy COS 3.5: Protect underground water supplies by enforcing controls on sources of pollutants.	Developer claims consistency because the BESS complies with adopted standards. However, the BESS threatens groundwater because it is susceptible to deflagration and the release of heavy metals into the soil during deflagration and into the groundwater during fire suppression.
Policy COS 4.1: Direct the majority of the unincorporated Antelope Valley's future growth to rural town centers and economic opportunity areas, minimizing the potential for habitat loss and negative impacts in Significant Ecological Areas.	Developer claims consistency because the BESS is not in an SEA and the 500 kV transmission line "falls in line" with the Vincent Substation. However, the BESS and transmission line substantially controvert this policy by increasing wildfire risks to the SEA and thereby posing a significant threat to habitat and biological diversity. These impacts are exacerbated because insufficient water resources are available to suppress the fires that will frequently erupt at the BESS site.
Policy COS 4.2: Limit amount of potential development in Significant Ecological Areas, through appropriate land use designations with very low residential densities.	The BESS creates an industrial, 243 foot high non-residential transmission line in an SEA and it threatens the SEA with an ignition prone BESS and wildfire-susceptible transmission line.
Policy COS 4.3: Require new development in Significant Ecological Areas to comply with applicable Zoning Code requirements, ensuring that development occurs on the most environmentally suitable portions of the land.	The BESS controverts this policy because the 500 kV transmission line that will be located in and SEA is not a permitted use in agricultural zones, so it does not comply with the zoning code.
Policy COS 4.5: Require new development to provide adequate buffers from preserves, sanctuaries, habitat areas, wildlife corridors, State Parks, and National Forest lands.	The BESS violates this policy because it provides no buffers for the SEA that is immediately adjacent to it and because the transmission line (which is in the SEA and violates the Zoning Code) has no buffers.
Policy COS 4.6: Encourage connections between natural open space areas to allow for wildlife movement.	Developer claims consistency because the BESS is located between two transportation corridors. This is incorrect; much of it is adjacent to SEA open space. The BESS also does not comply because it eliminates open space and provides no wildlife connections.
Policy COS 4.8: Ensure ongoing habitat preservation by coordinating with California Fish and Wildlife to obtain information on threatened and endangered species.	Developer claims compliance because of communications with the Department of Fish and Wildlife. However, the BESS *does not* "ensure ongoing habitat preservation" because it destroys 70+ acres of habitat; also, conversations do not constitute compliance.

Policy COS 4.10: Restrict development that would reduce size of water bodies and minimize potential for loss of habitat and water supply.	The BESS destroys an extensive habitat area adjacent to the Santa Clara River headwaters, and its propensity for deflagration threatens habitat in the Santa Clara River.
Policy COS 5.2: Except within economic opportunity areas, limit the amount of potential development in Scenic Resource Areas through appropriate land use designations with very low densities to minimize negative impacts.	The BESS controverts this policy because it is a development outside an economic opportunity zone that is in a Scenic Resource Area which does not comply with the underlying land use designation and is a high density industrial use that creates many significantly negative impacts.
Policy COS 5.7: Ensure that incompatible development is discouraged in designated Scenic Drives by developing and implementing development standards and guidelines for development within identified viewsheds of these routes (Map 4.2: Antelope Valley Scenic Drives).	The Developer claims this policy is irrelevant because the BESS site "is not in a designated Scenic Drive". This is incorrect because this policy pertains to ***viewsheds*** of scenic drives. The BESS is adjacent to, and in the viewshed of, 2 scenic drives and it completely destroys these viewsheds; thus, it definitively and substantially controverts this policy.
Policy COS 9.2: Develop multi-modal transport systems that offer alternatives to auto travel to reduce vehicle trips, including regional transportation, transit, bicycle routes, trails, and pedestrian networks.	Developer claims consistency because the BESS is "remotely operated". However, the BESS does not offer a multi modal transport system; furthermore, it fails to comply because it *reduces* trail and pedestrian networks by *eliminating* existing trails.
Policy COS 9.7: Encourage reforestation and the planting of trees to sequester greenhouse gas emissions.	Developer claims consistency because there is a "Landscaping Plan" but the BESS permanently "deforests" 70+ acres of native vegetation and it will not plant trees because of ignition risk (only small, low vegetation will be planted).
Policy COS 10.1: Encourage the use of non-hazardous materials in utility-scale renewable energy production facilities to prevent leaching of potentially dangerous run-off materials into soils and watersheds.	The BESS substantially controverts this policy because the BESS units consist of thousands of tons of hazardous materials that will release hazardous materials into the air, soil, and groundwater with every deflagration event.
Policy COS 13.1: Direct utility-scale renewable energy production facilities, such as solar facilities, to locations where environmental, noise, and visual impacts will be minimized.	The BESS is not located where environmental impacts are minimized; to the contrary, the location in a rural residential area maximizes the noise, aesthetic, wildfire, public safety, and land use impacts that it creates.
Policy COS 13.3: Require all utility-scale renewable energy production facilities to implement a decommissioning plan, with full and financial guarantee instruments that will restore the full site to its natural state upon complete discontinuance of operations.	The "Decommissioning Plan" indicates footings and thousands of "slab on grade" concrete foundations below 3 feet will be "abandoned in place" which will impair native vegetation growth; it proves the site *will not* be restored to a "natural state".

Policy COS 13.5: Where utility-scale energy facilities cannot avoid sensitive biotic areas, require open space dedication in SEAs.	Developer claims consistency because the BESS "will comply" but the Application does not identify the size of the open space dedication or where it will be located (it merely states that "up to" 71 acres will be set aside).
Policy COS 13.6: Ensure utility-scale renewable energy production facilities do not create land use conflicts with adjacent agricultural lands or existing residential areas.	The BESS is a high density industrial use in a rural residential area and is thus intrinsically in conflict with adjacent agricultural lands and residential areas; these conflicts cannot be eliminated by buffering or development standards.
Policy COS 13.7: Limit aesthetic impacts of utility-scale energy facilities to preserve rural character.	The BESS is a utility scale energy facility with high density industrial facilities that obliterate rural character; its aesthetic impacts *cannot* be limited.
Policy COS 14.1: Require transmission lines to be place underground when feasible.	The BESS 500 kV transmission line could easily be placed underground, but it is not.
Policy COS 14.2: If new transmission lines cannot be placed underground, require they be collocated with existing transmission lines, or along existing transmission corridors when feasible.	The aboveground BESS 500 kV transmission line will cut a new transmission corridor and roads through the Santa Clara River SEA
Policy COS 14.3: If new transmission lines cannot be feasibly placed underground or collocated with existing transmission lines or along existing transmission corridors due to physical constraints, direct transmission lines to locations where visual and environmental impacts will be minimized.	The wildfire-prone 500 kV transmission line could be placed underground but instead will be constructed entirely in an SEA within a VHFHSZ and will have 243 foot high towers. Therefore, it will result in significant visual and environmental impacts that cannot be minimized.
Policy COS 14.4: Discourage the placement of new transmission lines on undisturbed lands containing sensitive biotic communities.	The BESS 500 kV transmission line will be constructed almost entirely on undisturbed land in an SEA that contains sensitive biotic communities and thus controverts this policy.
Policy COS 14.5: Discourage placement of new transmission lines through existing communities or properties with existing residential uses.	The BESS 500 kV transmission line runs through the community of Acton and is located on properties with existing residential uses; thus, it controverts this policy.
Policy COS 14.6: Review all proposed transmission line projects for conformity with the Goals and Policies of the AV Area Plan, including those listed above. When the California Public Utilities Commission is the decision-making authority for these projects, provide comments regarding conformity with the Goals and Policies of the Area Plan.	The developer claims consistency because the BESS will comply with CPUC General Orders; however, compliance with CPUC General Orders is irrelevant, The BESS transmission line is facially inconsistent with this policy because it does not conform with any applicable AV Area Plan Goal or Policy.

Policy COS 16.1: Except within Economic Opportunity Areas, require development to minimize removal of native vegetation. Discourage clear-scraping of land and ensure a large percentage of land is left in its natural state.	Developer claims consistency because the BESS removes vegetation for "fire protection and defensible space"; however, this policy is intended to *preserve* native vegetation. It is utterly controverted by the BESS which *clear scrapes* vegetation and leaves *nothing* in its natural state.
Policy PS 1.2: Require new developments provide sufficient access for emergency vehicles and sufficient evacuation routes for residents and animals.	The BESS controverts this policy by eliminating an existing secondary access route that is used by emergency vehicles and which provides residential evacuation opportunities.
Policy PS 3.1: Limit the amount of potential development in Flood Zones designated by the Federal Emergency Management Agency through appropriate land use designations with very low residential densities.	Developer claims this policy is not applicable because the BESS "is not within a Flood Zone". However, the BESS Transmission Line *is* in a Flood Zone (Figure 3.15-41) and because it does not have a "very low residential density", it does not comply.
Policy ED 1.10: Promote small-scale, household based renewable energy systems to enable Antelope Valley residents to become energy independent.	Utility scale energy projects like the BESS *substantially controvert* this policy by *disincentivizing* household based energy projects. This is because California now compels all customers to pay a fixed fee on their electrical bill to cover the cost of utility scale projects (like the BESS) *even though customers with household-based renewable energy systems do not use power from such projects*. The BESS *does not* promote small-scale, household based renewable energy systems; to the contrary, it disincentivizes them.
Policy ED 1.11: Encourage development of utility-scale renewable energy projects at appropriate locations to ensure any negative impacts are sufficiently mitigated.	The BESS facially violates this policy because it is in a location that will create significant aesthetic, noise, public safety, and economic impacts on local residents *which cannot be mitigated.*
Land Use Objective: Agricultural, equestrian, and animal keeping uses are allowed in Acton's Rural Town Areas provided Zoning Code requirements are met (Page COMM-5 of attached Document 3).	The BESS is located in Acton's Rural Town Area but it is not consistent with this Land Use Objective because it is not an agricultural or equestrian or animal keeping use and it does not meet Zoning Code requirements.
Land Use Objective: The intent and purpose of the "Rural" Land Use designation is to provide for "Single-family residences, equestrian and limited animal uses, and limited agricultural activities" (Page LU-9 of attached Document 3).	The BESS is not consistent with this Land Use Objective because it is not a single-family residence or an equestrian or limited animal use and it does not support a limited agricultural or related activity.

Land Use Objective: The intent and purpose of industrial uses is to serve local residents (Page LU-7 of attached Document 3).	The BESS is not consistent with this Land Use Objective because it is an industrial use that does not serve local residents.
Land Use Objective: The intent and purpose of the industrial lands in Acton is to provide local employment opportunities (Page COMM-4 of attached Document 3).	The BESS is not consistent with this Land Use Objective because it is an industrial use that does not provide local employment opportunities.
Land Use Objective: The Establishment of industrial uses in Acton that are outside of Industrial Zones is not compatible with community character and is strongly discouraged (Page COMM-5 of attached Document 3).	The BESS facially violates this Land Use Objective because it establishes a heavy industrial use on land that is not zoned for any industrial use; therefore, the BESS is, by definition, intrinsically incompatible with Acton's community character.

General Plan Policies That Were Adopted To Mitigate Environmental Impacts And Which Are Controverted By The Proposed BESS.

The General Plan record demonstrates that most General Plan policies, goals, and development objectives were adopted for the purpose of avoiding or mitigating environmental impacts. For instance, the General Plan Mitigation and Monitoring Program states that the adopted goals and policies will "preserve rural character" by limiting "incompatible" development (page 8 of the General Plan MMRP - relevant excerpts are provided in attached Document 5); this is reiterated on page 1-8 of the Draft EIR incorporated into the Final EIR. The Draft EIR also explains that virtually every General Plan goal and policy was adopted to reduce aesthetic, air quality, land use incompatibilities, and noise impacts (pages 5.1-11 to 5.1-15, 5.1-20, 5.1-27, 5.3-18 to 5.3-27, 5.10-13 to 5.10-32, and 5.12-56 to 5.12-57 of the Draft EIR). These citations are too voluminous to include in this filing; thus, they are incorporated herein by reference[5].

The Final EIR adopted for the General Plan also states that General Plan goals, policies and programs will "protect areas with hazard, environmental and resource constraints" (page 2-14 of the General Plan Final EIR - relevant excerpts are provided in attached Document 6), and the CEQA Findings of Fact adopted by the Board states that adherence to the policies of the General Plan would result in impacts which are "less than significant" and that policies were developed to reduce fire hazards and "minimize wildland fire" impacts (pages 31-32 of the adopted General Plan CEQA Findings of Fact - relevant excerpts are provided in attached Document 7). Accordingly, each General Plan policy, goal, or development objective that is controverted by the proposed BESS and which addresses land use incompatibilities, scenic resources, noise, rural preservation, and air quality or which pertains to areas that have environmental

[5] The County General Plan Draft EIR that was incorporated as part of the Final EIR is found here: https://planning.lacounty.gov/wp-content/uploads/2022/11/gp_2035_deir.pdf.

constraints (i.e., Significant Ecological Areas) or pose hazards (i.e., VHFHSZs) constitutes a potentially significant environmental impact. SORT found notes at least 20 such inconsistencies; they are summarized in Table 2.

Table 2. County General Plan Policies that are Controverted by the BESS Project.

General Plan Policy/Goal/Objective	Reason for Inconsistency
Policy LU 3.2: Discourage development in areas with high environmental resources and/or severe safety hazards.	The BESS introduces an explosion and fire-prone industrial development in a VHFHSZ.
Policy LU 6.1: Protect rural communities from encroachment of incompatible development that conflict with existing land use patterns and service standards.	The BESS introduces a high density heavy industrial development on agricultural land in a rural, bucolic residential neighborhood.
Policy LU 6.2: Encourage land uses and developments that are compatible with the natural environment and landscape.	The BESS is a high density, heavy industry development that is intrinsically incompatible with the existing natural, rural environment.
Policy LU 6.3: Encourage low density and low intensity development in rural areas that is compatible with rural community character, preserves open space, and conserves agricultural land.	The BESS is a high density, heavy industry development in a rural area and it is intrinsically incompatible with the surrounding rural character; it also eliminates open space and agricultural land.
Policy LU 10.9: Encourage land uses and design that stimulate positive and productive human relations and foster the achievement of community goals.	The BESS does not stimulate positive or productive human relations: it operates autonomously, it eliminates trails, and it thwarts rural community preservation goals.
Policy M 2.7: Require sidewalks and trails to accommodate existing and projected volumes of pedestrian, equestrian and bicycle activity.	The BESS eliminates existing trails and pedestrian pathways and does not accommodate pedestrian/ equestrian uses.
Policy M 2.8: Connect trails and pedestrian paths to schools, public transport, employment centers, shopping, residential neighborhoods, and other destinations.	The BESS eliminates existing pedestrian and equestrian trails that currently connect area residences to the rest of the Community.
Policy AQ 1.1: Minimize health risks to people from industrial toxic or hazardous air pollutant emissions, with an emphasis on local hot spots, such as existing point sources affecting immediate sensitive receptors.	The BESS increases health risks by introducing a fire-prone industrial use which, upon deflagration, emits hazardous air pollutants that immediately endanger all the sensitive receptors in the surrounding area.
Policy C/NR 1.2: Protect and conserve natural resources, natural areas, and available open spaces.	The BESS eliminates existing natural resources, natural areas, and open spaces adjacent to two scenic resource areas.

Policy C/NR 3.8: Discourage development in areas with identified significant biological resources, such as SEAs	The BESS includes a massive high voltage electrical transmission line that runs more than a mile through a protected SEA.
Policy C/NR12.3: Encourage distributed systems that use existing infrastructure and reduce environmental impacts.	The BESS is a utility scale energy project which, *by definition*, supplants and discourages distributed energy systems.
Policy C/NR 13.1: Protect scenic resources through land use regulations that mitigate development impacts.	The BESS controverts this policy because it is a development that violates all land use regulations that were adopted to mitigate development impacts and it decimates all scenic resources in the vicinity of the BESS.
Policy C/NR 13.4: Encourage developments to be designed to create a consistent visual relationship with the natural terrain and vegetation	The BESS is a massive, walled, heavy industrial use that has no visual relationship with natural terrain or vegetation, and it heavily alters and removes both.
Policy P/R 4.3: Develop a network of feeder trails into regional trails.	The BESS eliminates existing feeder trails.
Policy N 1.1: Utilize land uses to buffer noise-sensitive uses from sources of adverse noise impacts.	The BESS provides no land uses to buffer surrounding sensitive receptors from the adverse noise impacts that it creates.
Policy N 1.2: Reduce exposure to noise impacts by promoting land use compatibility.	The BESS is an incompatible industrial land use that *increases* noise impact exposures.
Policy N 1.11: Maximize buffer distances and design and orient sensitive receptor structures (hospitals, residential, etc.) to prevent noise and vibration transfer from commercial/light industrial uses.	The BESS is a heavy industrial use that will result in significant noise transfers to surrounding sensitive residential receptors because it cannot be designed to prevent low frequency noise insults or A-weighted noise insults to sensitive receptors that have a direct "line of sight" to the BESS facilities.
Policy PS/F 1.1: Discourage development in areas without adequate public services and facilities	The BESS project completely controverts this policy because it is located where there is no municipal water service. And, even if water service were brought to the site, the local municipality has insufficient water resources to continuously suppress the frequent and lengthy fires that will erupt at the BESS. Also, the local fire station in Acton is small, the nearest hazmat response team is more than 45 minutes away, and Los Angeles County Fire Department is already understaffed[6].

[6] GovTech.com reported in January, 2025 that the Los Angeles County Fire Department staffing ratio is 1.16 firefighters per 1000 residents [https://www.govtech.com/em/preparedness/some-major-california-fire-departments-are-understaffed]; this is much less than the average of 1.54 to 1.81 firefighters per 1,000 residents reported by NFPA [https://www.nfpa.org/education-and-research/research/nfpa-research/fire-statistical-reports/us-fire-department-profile].

Policy PS/F 6.7: Discourage above-ground electrical distribution and transmission lines *in hazard areas*.	The BESS 500 kV transmission line fully contradicts this policy because it is above-ground and located entirely in a VHFHSZ.
Policy PS/F 6.10: Encourage utility siting to be localized and *decentralized to reduce impacts*; reduce transmission losses; promote local conservation by connecting users to their systems more directly; and reduce system malfunctions.	The BESS expressly controverts this policy because it is not a localized or decentralized energy development. It is just the opposite and therefore creates transmission losses, does not promote or facilitate direct connections between users and their systems, and its lithium battery chemistry ensures frequent and dangerous system malfunctions.

Conclusion

The facts above demonstrate that the proposed BESS is inconsistent with more than 60 General Plan goals, policies, and development objectives that were adopted for the purpose of mitigating impacts; therefore, each of these inconsistencies constitutes a potentially significant environmental impact that must be addressed as part of the Commission's CEQA review of the proposed BESS development.

ATTACHMENT 12

SORT COMMENT LETTER FILED IN THE DOCKET JANUARY 5, 2026

SAVE OUR RURAL TOWN

January 5, 2026

Lisa Worrall, Project Manager
California Energy Commission
715 P Street, MS-40
Sacramento, CA 95814
Electronic filing of one 18 Page Letter and 1 Attachment.

Subject: Supplemental Comments by Save Our Rural Town (SORT).

Reference: AB-205 Application Submitted for a Proposed Battery Energy Storage Project in Acton, CA.
Docket Number 25-OPT-02.

Dear Ms. Worrall;

Save Our Rural Town (SORT) respectfully submits the following comments to the California Energy Commission (Commission) pursuant to the referenced licensing Application filed in Docket 25-OPT-02 for a proposed Battery Energy Storage System (BESS project or BESS development) in the rural community of Acton. The comments presented herein address deficiencies noted in the revised application submitted on October 15, and in particular, they focus on insufficiencies in the alternatives analysis (which is so narrowly constrained that it is inadequate for the purposes of the California Environmental Quality Act - CEQA) and in discussions pertaining to water resources and socioeconomic/net benefits impacts. Additionally, comments pertaining to emergency access concerns and the "Community Benefit" agreement plan are provided.

THE APPLICANT'S ALTERNATIVES DO NOT COMPLY WITH CEQA.
As SORT explained in prior correspondence, the BESS development will result in significant and unmitigable public safety, wildfire, hazardous material, air quality, transportation, noise, aesthetic (visual resource), waste management, water resource, and land use/zoning impacts. Despite SORT's factual representations, the Revised Application submitted by the developer asserts that the BESS project will not result in

any potentially significant environmental impacts[1]; this implies that the BESS could be approved with a Mitigated Negative Declaration (MND)[2] and does not require an alternatives analysis or an Environmental Impact Report (EIR). Nonetheless, and in response to Commission directives, the developer expanded the Revised Application to addressed six different BESS Project configurations; however, and as explained below, none of these alternatives suffice for the purposes of CEQA.

The purpose of alternatives analyses under CEQA is to develop a range of reasonable alternatives to the project or to the location of the project "which would feasibly attain most of the basic objectives of the project but would avoid or substantially lessen any of the significant effects of the project" [CEQA Guidelines 15126.6]. Thus, alternative project configurations and alternative project locations that do not "avoid or substantially lessen" any the significant effects of a proposed project ***are not*** "Alternatives" for the purposes of CEQA. SORT has analyzed the six alternatives presented in the Revised Application, and found that ***none of them*** qualify as "Alternatives" pursuant to CEQA because ***none of them*** "avoid or substantially lessen" the significant effects that will be created by the BESS project, towit:

<u>Peaceful Valley (Alternative 2):</u>
The Peaceful Valley Alternative shifts the BESS project north; SORT believes it involves Parcel Numbers 3057-006-030, 3057-008-040, 3057-010-011, 3057-010-012, 3057-010-013, 3057-010-014, 3057-010-030, 3057-010-037, 3057-010-040, 3057-010-053, 3057-010-054, and 3057-010-059[3]. The Peaceful Valley alternative places thousands of deflagration-prone lithium BESS containers on land that is agriculturally zoned, is adjacent to an existing residential neighborhood, is within a Very High Fire Hazard Severity Zone, is in east Acton (where high winds occur in fire weather conditions), and is visible from the 14 freeway and the Angeles Forest highway (both of which are designated Scenic Drives[4]). Therefore, the Peaceful Valley Alternative poses the same significant and unmitigable public safety, wildfire, hazardous material, air quality, transportation, noise, visual resource, waste management, water resource, and land use/zoning impacts as the BESS project. Because the Peaceful Valley Alternative does not "avoid or substantially lessen any of the significant effects" of the BESS project, it ***is not*** a legitimate CEQA alternative.

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[1] See for example page 4-4 of the application dated October, 2025.
[2] CEQA Guidelines Section 15070.
[3] The Applicant asserts that the Peaceful Valley Alternative involves 13 parcels, but SORT could only identify 12 parcels.
[4] https://www.arcgis.com/home/item.html?id=50518b2818dc4a2eb9bf1e8a7557f2a3

Reduced Project (Alternative 3):

The Reduced Project Alternative is identical to the proposed project, but provides a slight (17%) reduction in the size of the BESS yard. Because the Reduced Project Alternative involves the same type of facilities as the BESS project and is in the same location as the BESS project, it will create the same significant and unmitigable public safety, wildfire, hazardous material, air quality, transportation, noise, visual resource, waste management, water resource, and land use/zoning impacts as the BESS project without substantially lessening any of them[5]. And, while the Reduced Project Alternative may result in less frequent deflagration events than the BESS project, it *does not* lessen the significant public safety and wildfire effects that will occur with each BESS deflagration event. Because the Reduced Project Alternative does not "avoid or substantially lessen any of the significant effects of the BESS Project", it ***is not*** a legitimate CEQA alternative.

Crown Valley (Alternative 4):

The Crown Valley Alternative shifts the BESS project northwest onto Parcels 3217-026-051, 3217-026-052, 3217-026-025, 3217-026-026, and 3217-026-027. The Crown Valley alternative places thousands of deflagration-prone lithium BESS containers on land that is agriculturally zoned, is adjacent to an existing residential neighborhood, is within a Very High Fire Hazard Severity Zone, and is in north Acton (where high winds occur in fire weather conditions). It is not known whether the Crown Valley BESS location is visible from the 14 freeway (a designated Scenic Drive); however, the location is a beautiful rural valley (Figure 1) that will be forever marred by an enormous, industrial, utility-scale generation facility and a transmission substation. Therefore, the Crown Valley Alternative poses the same significant and unmitigable public safety, wildfire, hazardous material, air quality, transportation, noise, visual resource, waste management, water resource, and land use/zoning impacts as the BESS project. Because the Crown Valley Alternative does not "avoid or substantially lessen any of the significant effects" of the BESS project, it ***is not*** a legitimate CEQA alternative.

Tierra Subida (Alternative 5):

The Tierra Subida Alternative shifts the BESS project outside of Acton onto Parcels 3054-020-020, 3054-020-021, 3054-020-022, 3054-020-023, 3054-020-029, 3054-

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[5] The Applicant claims that the "Reduced Project Alternative" is located in a High Fire Hazard Severity Zone. This is incorrect. As indicated in adopted CalFire Maps, the "Reduced Project Alternative" is located in a Very High Fire Hazard Severity Zone. https://osfm.fire.ca.gov/what-we-do/community-wildfire-preparedness-and-mitigation/fire-hazard-severity-zones.

Figure 1. Photograph of the Site Proposed for the Crown Valley Alternative.

View from the vicinity of the intersection of Sand Creek Drive and 28th Street in Acton.

020-030, 3054-020-031, 3054-020-032, 3054-020-033, 3054-020-034, 3054-020-035, 3054-020-036, and 3054-020-901. The Tierra Subida alternative places thousands of deflagration-prone lithium BESS containers on land that is agriculturally zoned, is adjacent to an existing residential neighborhood, is within a Very High Fire Hazard Severity Zone, is adjacent to the 14 freeway (a designated Scenic Drive) and is in the northeast foothills of the Sierra Pelona Mountains (where high winds occur in fire weather conditions). Therefore, the Tierra Subida Alternative poses the same significant and unmitigable public safety, wildfire, hazardous material, air quality, transportation, noise, visual resource, waste management, water resource, and land use/zoning impacts as the BESS project. Because the Tierra Subida Alternative does not "avoid or substantially lessen any of the significant effects" of the BESS project, it ***is not*** a legitimate CEQA alternative.

Pearblossom (Alternative 6):

The Pearblossom Alternative shifts the BESS project out of Acton and onto Parcels 3052-027-027 and 3052-027-028. The Pearblossom alternative places thousands of deflagration-prone lithium BESS containers on land that is zoned for rural mixed uses, is adjacent to an existing residential neighborhood, is within a High Fire Hazard Severity Zone and adjacent to a Very High Fire Hazard Severity Zone, and is slightly north of the northern foothills of the San Gabriel Mountains (where high winds occur in fire weather conditions). It is not clear whether the Pearblossom location is visible from Barrel Springs Road (a designated Scenic Drive), but the transmission substation is will be seen from Cheeseboro Road (a designated Scenic Drive). In any event, the Pearblossom Alternative locates an enormous, industrial, utility-scale generation facility and a massive new transmission substation in a beautiful high desert landscape (Figure 2). Therefore, the Pearblossom Alternative poses the same significant and unmitigable public safety, wildfire, hazardous material, air quality, transportation, noise, visual resource, waste management, water resource, and land use/zoning impacts as the proposed BESS development. Because the Pearblossom Alternative does not "avoid or substantially lessen any of the significant effects" of the BESS project, it ***is not*** a legitimate CEQA alternative.

Figure 2. Photograph of the Site Proposed for the Pearblossom Alternative.

View of Pearblossom Alternative location taken from 47th Street looking northwest.

<u>Barrel Springs (Alternative 7):</u>

The Barrel Springs Alternative shifts the BESS project outside of Acton onto a single parcel in Palmdale (3048-008-003). The Barrel Springs alternative places thousands of deflagration-prone lithium BESS containers on land that is zoned for residential uses, is adjacent to an existing residential neighborhood, is within a Very High Fire Hazard Severity Zone, is adjacent to Barrel Springs Road (a designated Scenic Drive) and is in the northern foothills of the San Gabriel Mountains east of the Soledad Pass (where high winds occur in fire weather conditions). Therefore, the Barrel Springs Alternative poses the same significant and unmitigable public safety, wildfire, hazardous material, air quality, transportation, noise, visual resource, waste management, water resource, and land use/zoning impacts as the proposed BESS development. Because the Barrel Springs Alternative does not "avoid or substantially lessen any of the significant effects" of the BESS project, it ***is not*** a legitimate CEQA alternative.

THE DEVELOPER'S PROJECT OBJECTIVES ARE TOO CONSTRAINED TO PROVIDE A RANGE OF REASONABLE PROJECT ALTERNATIVES.

As SORT explained in previous correspondence, the Project Objectives established by the Developer do not comply with CEQA because they are so constrained that the only alternative which is capable of achieving most of them is the proposed BESS project[6]; therefore, the developer's Project Objectives preclude the consideration of "a range of reasonable alternatives" as required by CEQA[7]. Even the inadequate location alternatives presented in the revised Application are rejected because they are neither "near the Vincent Substation" nor "near existing roadways and infrastructure"[8]. Equally important, *there is no justification or evidentiary support for Project Objectives that require proximity to transmission substations and infrastructure*; in fact, many remote BESS and renewable generation facilities have been successfully interconnected to the CAISO transmission grid despite the fact that they are located miles from substations and infrastructure. For example, the Sanborn project (which is the largest BESS constructed to date) is nowhere near "existing infrastructure" (whatever that means) and it is 11 miles from the Windhub transmission substation to which it connects. Equally important, the "System Impact Study" and the "Facilities Study" prepared by CAISO and SCE for the BESS project were both predicated on the assumption that the BESS project was located *more than 24 miles from the Vincent substation*[9]. Accordingly, the Applicant's proposed Project Objectives that require adjacency to substations and infrastructure must be rejected because they are neither justifiable nor supported by substantial record evidence.

FEASIBLE ALTERNATIVES EXIST THAT WILL SUBSTANTIALLY LESSEN MANY SIGNIFICANT EFFECTS OF THE BESS PROJECT.

A number of feasible project alternatives are capable of achieving all CEQA-compliant project objectives while substantially lessening significant effects of the BESS Project. Such alternatives fall into two categories: System Alternatives and Location Alternatives.

System Alternatives

System Alternatives include alternatives to the Lithium-based battery chemistry that is proposed for the BESS project and which requires flammable electrolyte, is prone to spontaneous deflagration, and releases substantial quantities of toxic air pollutants

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[6] SORT Letter to the Commission dated August 18, 2025. At 66-67.
[7] CEQA Guidelines Section 15126.6.
[8] Pages 4-24, 4-33 to 34, 4-36, 4-39, and 4-42 of the Applicant's response titled "Data Request 2_Part 1".
[9] Pages 99 and 119 of the Large Generator Interconnection Agreement for the Angeleno Project.

when deflagration occurs. Non-lithium battery System Alternatives include Iron Flow, Vanadium Redox, Aqueous Zinc, etc. While these System Alternatives successfully achieve all CEQA-compliant project objectives established for the BESS, they also substantially lessen the significant effects of the BESS project. For example, the deflagration propensities of non-lithium System Alternatives are substantially lower than the proposed BESS; therefore, all these System Alternatives substantially lessen the public safety and wildfire effects of the BESS project. Non-lithium BESS can be constructed inside aesthetically pleasing structures and surrounded by landscaping. And, when coupled with an indoor substation that utilizes non-SF6 Gas Insulated Switchgear, all System Alternatives will substantially lessen visual resource impacts. Some System Alternatives can even be stacked and may therefore reduce the BESS project footprint. Finally, by carefully configuring these System Alternatives and the proposed 500 kV substation, noise impacts can also be reduced. Simply put, System Alternatives are entirely feasible, they achieve all permissible Project Objectives and they substantially lessen many of the significant effects of the BESS project. Accordingly, System Alternatives are all "Environmentally Preferred" compared to the BESS project.

The Application peremptorily rejects "Flow Battery Technology" as a possible project alternative because it has "lower energy and power densities requiring more space and additional equipment" and the developer alleges that it is "not a proven technology at the scale of the Project"[10]. These claims are specious:

- There are no Project Objectives pertaining to energy and power densities; therefore, System Alternatives cannot be rejected on the basis of energy and power densities.
- Some System Alternatives can be stacked and thus may result in a smaller footprint than lithium battery systems.
- Utility "Flow Battery" systems are operational[11], so the technology is "proven".
- The proposed BESS is twice as large as any BESS ever developed[12], so no battery technology is "at the scale of the Project" *including lithium battery technologies*.

There is no legitimate basis for rejecting System Alternatives, particularly since they substantially lessen the significant environmental effects of the BESS project.

[10] Page 4-18 of the Revised Application submitted into the Docket as "Data Request 2_Part 4".
[11] For example, ESS has long duration iron flow storage systems operating in Florida and Arizona.
[12] Currently, Sanborn is the largest constructed BESS, but it is half the size of the proposed BESS Project.

Location Alternatives

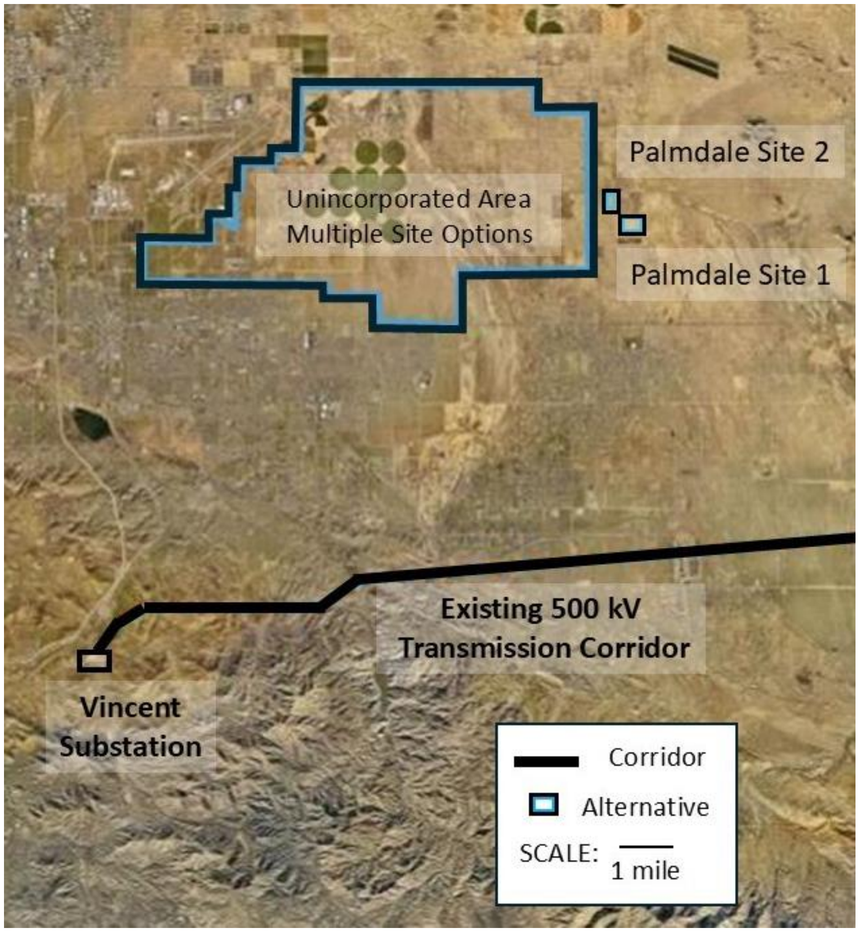
There are a number of alternative locations where the BESS Project could be feasibly constructed which will avoid or substantially lessen its significant environmental effects:

Alternative Location 1: The first alternative location that should be considered by the Commission is the location where the Applicant originally intended to construct the BESS Project[13]. SORT is not certain of the precise location of Alternative Location 1, but it is known that the BESS was intended to be in the middle of a 1,000+ MW solar farm which would necessarily require at least 6,000 acres and thus not be located near residences. Accordingly, "Alternative Location 1" is certain to substantially lessen the significant public safety and noise impacts posed by the proposed BESS project.

Alternative Location 2: The second alternative location that should be considered is a 26 square mile area in unincorporated East Antelope Valley that is designated for industrial purposes and where no residential uses are permitted. The area is depicted in Figure 3 and labeled as "Unincorporated Area"; it includes large tracts of vacant and irrigated lands that are adjacent to industrial uses and outside of mapped Significant Ecological Areas. These tracts are more than a mile from any residence, and since at least 1973, these lands have been designated as "Public and Semi Public lands" by the County General Plan. According to both the 1980 and the 2015 County General Plans, these tracts of land are "intended to be used for major utilities, transportation facilities, waste facilities, etc." The tracts are owned by the City of Los Angeles and they lie adjacent to aerospace facilities and an airstrip owned by the US Government (known as Air Force Plant 42). Locating the BESS within one of these tracts of land would substantially lessen the significant noise, visual resource, and public safety impacts of the BESS Project; it would also substantially lessen all significant impacts stemming from land use conflicts. Because nearly all of these tracts lie outside of high and very high fire hazard severity zones, Alternative Location 2 substantially reduces the significant wildfire impacts posed by the BESS Project. Furthermore, a transmission interconnection can be easily accomplished because Alternative Location 2 it is just 6 miles north of an existing 500 kV transmission corridor that terminates at the Vincent substation. The corridor has multiple single circuit 500 kV lines and, on the north side, a 220 kV line. By expanding the corridor or (better yet) upgrading the 220 kV line to a

[13] The location was considered in the System Facilities Study and System Impact Study that CAISO and SCE prepared in accordance with the CAISO Tariff. According to the "Large Generator Interconnection Agreement", it is 24.4 miles from the Vincent Substation [at 99 and 119].

Figure 3. Map of Feasible Location Alternatives.



double circuit configuration that serves both the 500 kV BESS and the existing 220 kV connection, the BESS can be connected to the Vincent substation's 500 kV bus. A photograph of this existing 500 kV corridor is provided in Figure 4.

This alternative is consistent with statutory Garamendi Principals[14], and the 220 kV upgrade alternative would not require significant expansion of an existing transmission corridor. There is also an extensive network of roads in the vicinity of Alternative Location 2; therefore, the connection between Alternative Location 2 and the 500 kV transmission corridor can be developed largely via local agency franchise agreements.

[14] Garamendi Principles, SB 2431, Stats. 1988, Ch. 1457. The Statute states in pertinent part that the Legislature "finds and declares that the construction of new high-voltage transmission lines within new rights-of-way may impose financial hardships and adverse environmental impacts on the state and its residents, so that it is in the interests of the state, through existing licensing processes, to accomplish all of the following: 1. Encourage the use of existing rights-of-way by upgrading existing transmission facilities where technically and economically justifiable. 2. When construction of new transmission lines is required, encourage expansion of existing rights-of-way, when technically and economically feasible."

Figure 4. Existing Transmission Corridor that terminates at the Vincent Substation.

SORT estimates that a 500 kV transmission interconnection between the Vincent substation and the Alternative Location 2 would be approximately 13 miles long and could be constructed for under $50 million[15]. This cost is marginal when compared to the $1.75+ billion in capital costs that the Applicant expects to incur[16]; accordingly, this alternative is economically "feasible" as that term is contemplated in CEQA[17].

Moreover, recent revisions to transmission line permitting processes implemented by the California Public Utilities Commission now allow SCE to sidestep traditional "Certificate of Public Convenience and Necessity" requirements and construct the 500 kV transmission connection with just a Permit to Construct[18].

[15] A $2.3 million per mile construction cost for the 500 kV line is reasonable because the lands where the new 6 mile segment is located is rural, flat, and unencumbered and because the transmission line could be constructed using franchise agreements and then connect to an existing transmission corridor.

[16] Page 3.10-19 of Application.

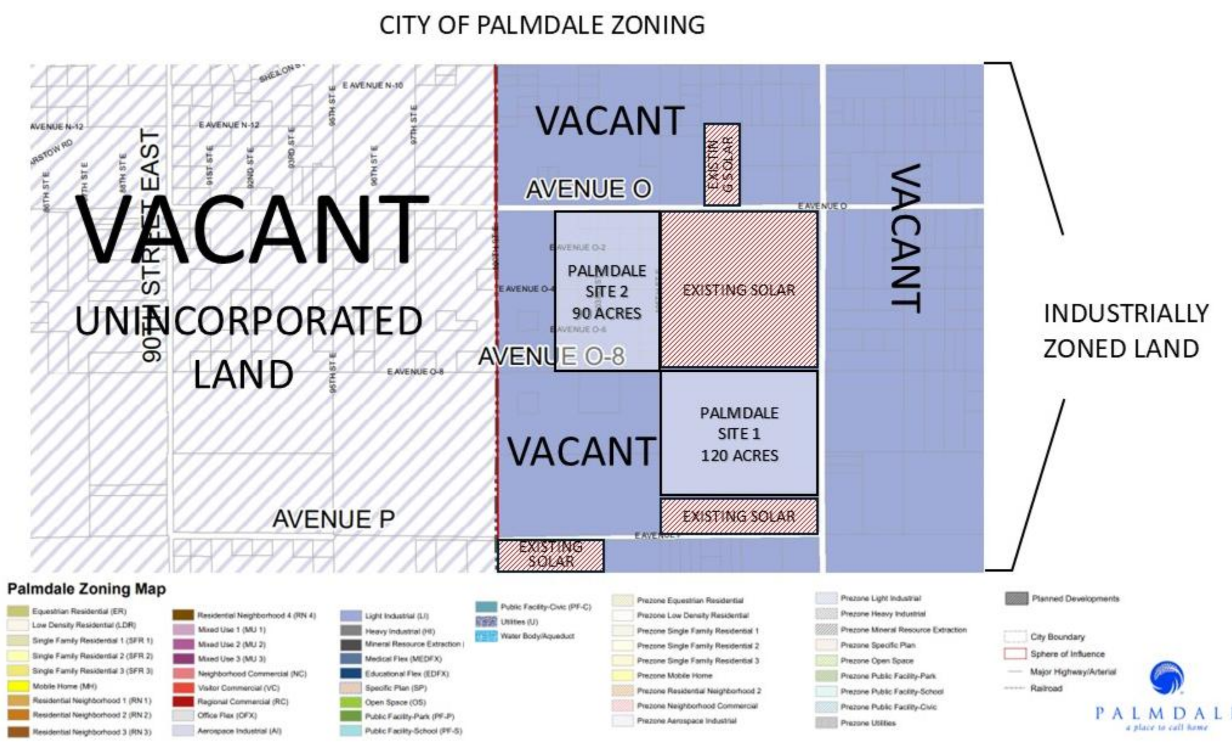
[17] The Courts have long held that a project alternative is economically feasible under CEQA even if it costs more than the proposed project. "The fact that an alternative may be more expensive or less profitable is not sufficient to show that the alternative is financially infeasible. What is required is evidence that the additional costs or lost profitability are sufficiently severe as to render it impractical to proceed with the project" [*Citizens of Goleta Valley v. Board of Supervisors*, (1988) 197 Cal.App.3d].

[18] The CPUC recently amended General Order 131 to authorize a new transmission line with just a Permit to Construct if the line interconnects a new generation facility (i.e., a BESS) to an existing electrical transmission facility (i.e. the Vincent Substation) because it is considered to be just an "extension" and not a new transmission line [GO 131-E.I.F.2.a].

Alternative Locations 3 and 4:

Other alternative locations in East Antelope Valley are in the City of Palmdale adjacent to the unincorporated "Public and Semi Public Lands" described above. These locations (depicted in Figure 3 as "Palmdale Site 1" and "Palmdale Site 2") are north of the existing transmission corridor described above; thus, interconnection to the Vincent substation can be accomplished largely with corridor modifications and franchise agreements. The sites are sufficiently large to accommodate a 30 acre BESS yard and 23 acre substation and are outside of any mapped Significant Ecological Areas. While portions of these sites have small drainage courses, there is sufficient space available to avoid these areas. These properties are thousands of feet from any residential structures reported on County property tax rolls and they are not in "High" or "Very High" Fire Hazard Severity Zones. As indicated in Figure 5, these parcels are zoned for industrial use and are adjacent to extensive utility scale solar facilities. Some of these parcels may be owned by the City of Los Angeles; others are privately held. Given the zoning on these sites, their separation from residential areas, and their CalFire designation, these Alternative Locations will substantially lessen the significant environmental effects posed by the BESS Project.

Figure 5: Details on Zoning and Land Uses for Alternative Locations 3 and 4.



Other Alternative Locations:

There are many other sites where the BESS can be located far from homes and outside of “High” and “Very High” Fire Hazard Severity Zones. For instance, the west side of the Antelope Valley has large tracts of vacant land that are close to existing 500 kV transmission corridors which terminate at the Vincent substation and are still great distances from residential neighborhoods. These areas are also near existing roadways where connections to the existing 500 kV transmission corridors can be achieved largely via local agency franchise agreements. Accordingly, alternative locations in the west Antelope Valley are similar in many ways to the alternatives discussed above. The area is largely zoned for agricultural purposes, so the BESS would still conflict with underlying land use designations; however, siting the BESS project in these areas will substantially lessen public safety, wildfire, noise, and visual resource impacts.

WATER RESOURCE CONCERNS

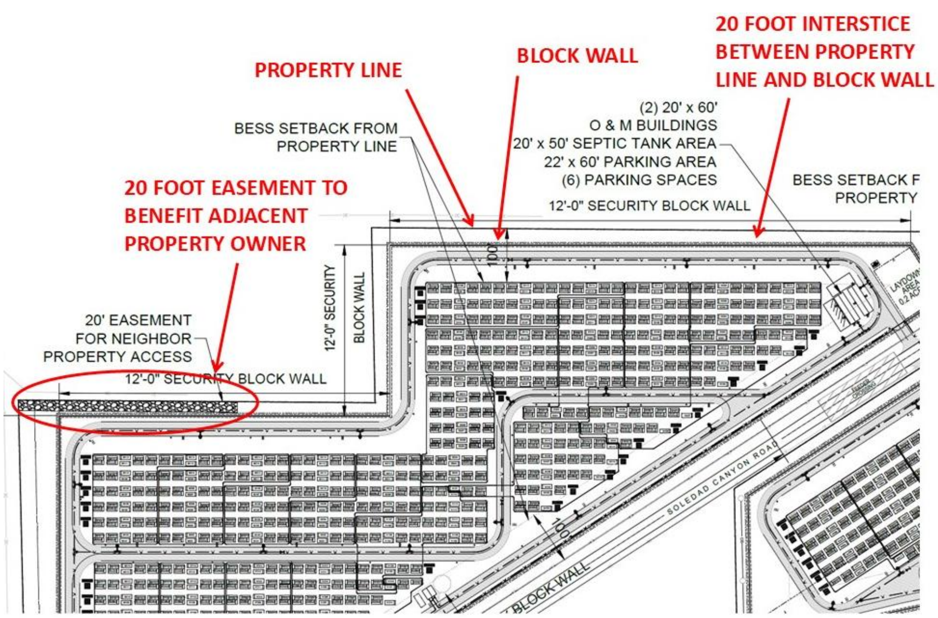
To satisfy the requirement imposed by Section 14(C)(v) of Appendix B “Information Requirements for an Application for Certification or Small Power Plant Exemption”, the Applicant submitted a “Construction Water Memo” on October 23, 2025. However, the “Construction Water Memo” does not satisfy the requirements imposed by Section 14(C)(v) of Appendix B[19] because it only addresses water resources that will be utilized during construction and it ignores the substantial quantities of water that will be required to safely operate the project. In particular, the “Construction Water Memo” fails to account for the hundreds of thousands of gallons of water that will be needed to control each BESS deflagration event that will occur. And, given the massive size of the BESS project (involving 2,000+ BESS containers stretching more than a mile), deflagration events will occur often. As SORT explained in previous correspondence[20], the existing domestic water well that will supply water for BESS project operations may be suitable for sanitary purposes, but it is entirely incapable of serving BESS Project fire protection needs because it lacks sufficient capacity to continually pressurize all the fire hydrants required throughout the BESS yard[21]. Accordingly, the Application is still incomplete and it will remain incomplete until this significant deficiency is addressed.

[19] These requirements are: For all water supplies intended for industrial uses to be provided from public or private water purveyors, a letter of intent or will-serve letter indicating that the purveyor is willing to serve the project, has adequate supplies available for the life of the project, and any conditions or restrictions under which water will be provided. In the event that a will-serve letter or letter of intent cannot be provided, identify the most likely water purveyor and discuss the necessary assurances from the water purveyor to serve the project.
[20] SORT Letter to the Commission dated August 18, 2025. At 59-60.
[21] SORT believes the County Fire Department will require a network of fire hydrants in the BESS yard.

ACCESS CONCERNS

The revised Application does not appear to address concerns raised by SORT pertaining to emergency access[22] and the fact that the BESS Project eliminates secondary access to adjacent residences. Recently, SORT learned that the primary access for adjacent residences is prone to erosion and is thus substandard; therefore, the BESS Project will eliminate the only reliable access route for Acton residents. This significantly adverse impact cannot be ignored, particularly since it can be easily mitigated. Specifically, the revised Site Plan[23] indicates that, along the northern wall surrounding the western the BESS yard, there is a 20 foot wide interstice between the property line and the block wall (see Figure 6). SORT presumes this interstitial area is intended for landscaping, but it could be configured and slightly widened to accommodate both landscaping and an access road that can be used by emergency vehicles and surrounding residents. The Applicant would provide an easement granting public access rights along, across, and over this access road. As Figure 6 shows, the developer proposes such an easement along the north wall to benefit one resident[24]; this easement should be extended to benefit other residents and, for trail purposes, it should surround the entire development (which will mitigate the trail impacts that SORT previously identified[25]).

Figure 6. Excerpt of Revised BESS Project Site Plan (Annotated in Red).



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[22] SORT Letter to the Commission dated August 18, 2025 at 48.
[23] This Revised Site Plan is found in Attachment 28 in the response titled "Data Request 2_Part 5" located here: https://efiling.energy.ca.gov/GetDocument.aspx?tn=266608&DocumentContentId=103665
[24] The revised site plan indicates a 20 foot easement will be granted "for neighbor property access".
[25] SORT Letter to the Commission dated August 18, 2025 at 35 and 49-52.

DEFICIENCIES IN THE SOCIOECONOMIC ANALYSIS.

The Applicant has revised Section 3.10 of the Application pertaining to Socioeconomic Impacts[26]; however, none of the deficiencies noted in our comments submitted in August, 2025 were addressed. For example, the Applicant persists in misrepresenting enrollment levels at the local school district. To be clear, the Acton-Agua Dulce Unified School District ***does not*** have 3,329 students enrolled in kindergarten through Grade 5, it ***does not*** have 1,694 students enrolled in Grades 6 through 8, and it ***does not*** have 7,852 students enrolled in Grades 9 through 12. These *facts* are enumerated in a letter prepared by the Superintendent of the AADUSD that is provided in Attachment 1; it explains that the total enrollment in the AADUSD is approximately 1,100 students. SORT respectfully recommends that the Commission direct the Applicant to revise the Socioeconomic Analysis and correct this and other deficiencies we previously identified.

DEFICIENCIES IN THE NET BENEFITS ANALYSIS.

SORT understands that the Commission has approved the Applicant's "Net Benefits" analysis despite the fact that it is rife with errors. For example, and as SORT explained in a previous comment letter, the AADUSD ***will never*** receive the $54.6 million in revenues over the life of the BESS project that is claimed by the Applicant's "Net Benefits Analysis" for all the reasons set forth in our previous correspondence[27] all of which are incorporated herein by reference. SORT respectfully recommends that the Commission direct the Applicant to revise the Net Benefits Analysis to correct this and other errors we previously identified.

DEFICIENCIES IN THE COMMUNITY BENEFITS AGREEMENT PLAN.

SORT understands that the Commission is satisfied by the Applicant's "Community Benefits" agreement plan prepared for the BESS project. Nonetheless, the plan does not comply with AB 205 because it does not involve or benefit organizations based in the Community of Acton where the BESS Project is located.

While AB205 provides few specifics regarding "Community Benefit" agreements, it does compel developers to enter into contracts with, or that benefit, "community-based" organizations which "represent community interests"[28]. Because AB205 does not define "community", and because the legislative record sheds no light on what lawmakers

[26] See Attachment 18 found in the response titled "Data Request 2_Part 4".

[27] SORT letter to the Commission dated August 18, 2025 at 26.

[28] AB 205 requires the Applicant to enter into legally binding agreements "with, or that benefit, a coalition of one or more *community-based organizations"* that *"represent community interests*, where there is mutual benefit to the parties to the agreement" (emphasis added).

intended when they restricted such agreements to benefit only "community-based" organizations that "represent community interests [29]", the rules of statutory construction must be applied to ensure proper implementation of AB205.

First, words must be given their plain and ordinary meaning. The Merriam-Webster Dictionary defines the term "Community" to mean "a unified body of individuals such as people with common interests living in a particular area and, broadly, the area itself" and it clarifies that communities exist "*within* a larger society". Consistent with this definition, Acton is clearly a "community" and it exists within the larger "society" of Los Angeles County.

Second, interpretations must give harmonious effect to the statute as a whole, and interpretations that leads to absurd results must be avoided. Therefore, the AB 205 requirement that a developer provide benefits to one or more community based organizations which represent community interests must be harmonized with the AB 205 directive to the Commission to approve a project that substantially benefits the developer if the project meets all applicable requirements at the location within the community where it is proposed. In other words, AB 205 can only be interpreted to mean that the organization which benefits from the developer agreements mandated by AB 205 must represent the interests of the community that is burdened by the adverse impacts of the AB 205-approved project; any other interpretation would lead to absurd outcomes[30]. Accordingly, SORT recommends that the Commission apply the following two pronged test to assess whether a "Community Benefit" agreement plan complies with AB 205: 1) Are the agreements it enumerates with, or do they benefit, organizations that are based in the community where the project is located? and 2) Do these organizations represent the interests of the community where the project is located?

Application of this two pronged test to the BESS Project "Community Benefits" agreement plan demonstrates that the plan does not comply with AB 205 because it does not involve or benefit Acton-based organizations and because the organizations that it does benefit do not represent Acton Community interests. The plan does not

[29] SORT requested a copy of the legislative record for Assembly Bill 205 from the California State Archives; SORT was informed that the State Archives have no records pertaining to Assembly Bill 205.
[30] It would be absurd to construe AB 205 to mean that the very community which bears all the adverse impacts of AB 205-approved projects should be entirely omitted from the benefit plan. It would be equally absurd to construe AB205 to mean that an organization should benefit from an AB 205-approved project even though it does not represent the interests of the community that is burdened by the project. These absurd scenarios imply that the legislature did not care *which* community received benefits as long as *some* community did; such interpretations render the "community benefit plan" provisions of AB 205 pointless and meaningless, and thus invalid under the rules of Statutory Construction.

even mention the Community of Acton, and is instead called the "*Antelope Valley and Los Angeles County Community Benefits Agreement Plan*"[31]. Notably, neither Los Angeles County nor the Antelope Valley ***are*** "communities"; to the contrary, they are geographic regions that exceed 1,000 square miles in area and encompass hundreds of communities (both incorporated and unincorporated). Moreover, the Application demonstrates that the developer has never even engaged any "community based" organizations because it states that only "county based" organizations were engaged to develop the plan[32] and that these "county based" organizations represent a multiplicity of communities[33]. Furthermore, the BESS Project "Community Benefits" agreement plan does not identify any Acton-based organizations and it certainly does not explain how it benefits any Acton-based organizations.

Instead, the plan asserts that the developer will only be investing in programs that align with Los Angeles County and Antelope Valley priorities, not Acton priorities[34]. For instance, the plan explicitly states that developer investments will 1) "deliver training and job readiness" across the Antelope Valley and, more broadly, across Los Angeles County[35]; 2) provide backup generation for "hospitals and emergency response infrastructure" (Acton has no hospital and our emergency response infrastructure already has backup generation)[36]; 3) support open space conservation across Los Angeles County and the high desert[37]; and 4) expand energy education and workforce training throughout Los Angeles County[38]. And, while the BESS Project "Community Benefits" agreement plan states that the developer will coordinate with "Township and Los Angeles County representatives", it clarifies these efforts will respond to pressing needs in the "region"[39], *not the "community".* Because the investments commitments made by the BESS Project "Community Benefits" agreement plan do not benefit Acton-based organizations that represent Acton Community interests, the plan *does not* satisfy the community benefit requirements imposed by AB 205. Accordingly*, the BESS Project "Community Benefits" agreement plan* ***will not*** *withstand judicial review.*

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31 Appendix 1B of the Application at page 1.
32 Section 1.6.7 of the Application explicitly states "The Applicant has been meeting with multiple *County-based* community organizations and will be meeting with additional *County-based* organizations to better understand their immediate and long-term needs" (emphasis added).
33 Section 1.6.7 of the Application explains that "county based" organizations represent and support the broader interests of multiple communities.
34 Appendix 1B of the Application at page 1.
35 Id at 2.
36 Id at 3.
37 Idem.
38 Idem.
39 Idem.

The BESS Project "Community Benefits" agreement plan describes one contractual agreement in detail, and it exemplifies how the plan controverts AB 205 requirements by failing to involve or benefit any Acton-based organizations representing Acton interests. Specifically, the plan explains that the Applicant signed a contract with the "Los Angeles/Orange County Building & Construction Trades Council" ("LA/OCBCTC") which is an organization representing labor union interests in Los Angeles County and Orange County[40]; SORT has confirmed that LA/OCBCTC is not an Acton-based organization, it has no presence in Acton, it has no members in Acton, and it does not represent any Acton Community interests[41]. The plan further explains that the designated beneficiary of this contract is a subset organization called "Women in Non-Traditional Employment Roles" or "WINTER[42]; however, "WINTER" is not an Acton-based organization, it has no presence in Acton, it has no members in Acton, and it does not represent Acton Community interests. Accordingly, neither the contract with LA/OCBCTC nor the designated beneficiary arrangement with "WINTER" suffice for AB 205 purposes.

The fatal flaw in the BESS Project "Community Benefits" agreement plan stems from the Applicant's failure to acknowledge that the BESS Project lies squarely within the Community of Acton; in fact, the Application falsely claims that the BESS project lies far outside of Acton[43]. Such mendacities allows the Applicant to pretend that the BESS Project is not located within any particular community and, by extension, that the BESS Project "Community Benefits" agreement plan need not benefit any particular community and can instead accrue general benefits across all communities in Los Angeles County. The Commission cannot similarly pretend. The BESS Project ***is*** located in a specific community (Acton); therefore, benefits conferred by the BESS Project "Community Benefits" agreement plan **must** accrue to Acton-based organizations that represent Acton community interests. Because the BESS Project "Community Benefits" agreement plan fails to benefit Acton-based organizations representing Acton community interests; it does not comply with AB 205 requirements.

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[40] LA/OCBCTC is headquartered at 1626 Beverly Blvd in Los Angeles [https://laocbuildingtrades.org/].
[41] On July 21, 2025, the Director of SORT spoke with a principal at LA/OCBCTC and confirmed that LA/OCBCTC has no members in Acton and that the members who will benefit from the agreement live outside of Acton (specifically, they live in Palmdale, Lancaster, and Santa Clarita). The LA/OCBCTC representative also explained that Acton should not benefit from the BESS Project "Community Benefits" agreement plan because Acton is not a city, and that Acton could perhaps benefit indirectly from the agreement because it will benefit Los Angeles County "at large". SORT's Director asked how the Acton community benefits from temporary jobs taken by workers living outside of Acton; there was no response.
[42] Appendix 1B of the Application at page 1.
[43] The Application states the BESS Project is "three (3) miles northeast" of Acton. Page 2-1.

In pointing out these flaws, SORT is not arguing that the contracts and financial commitments set forth in the BESS Project "Community Benefits" agreement plan are inappropriate or unacceptable; to the contrary, SORT does not object to them. SORT's purpose is to demonstrate why the BESS Project "Community Benefits" agreement plan does not comply with AB 205 requirements and, by extension, why it will not withstand judicial review.

To correct these fatal deficiencies, SORT recommends the Applicant acknowledge that the BESS Project is located in the Community of Acton, and then initiate authentic community engagement with Acton organizations and residents as recommended by the Acton Town Council[44]. These meetings will enable the Applicant to collaboratively develop a BESS Project "Community Benefits" agreement plan that complies with AB 205 by delivering benefits to authentic Acton-based organizations which represent authentic Acton community interests. Another option is for the Applicant to work with authentic Acton organizations that represent authentic Acton interests to establish a Community Foundation consistent with recent revisions to AB 205[45].

CONCLUSION

For the reasons set forth above, SORT respectfully requests that the Commission direct the developer to amend the BESS project Application to address the deficiencies noted herein. We also request that the abovementioned concerns be factored into the Commission's consideration of the BESS Project. SORT is happy to discuss any of the concerns presented above and in our prior correspondence with Commission staff; SORT can be reached at SORTActon@gmail.com.

Respectfully Submitted;

/S/ Jacqueline Ayer
Jacqueline Ayer, Director
Save Our Rural Town

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[44] In a letter to the Commission dated September 3, 2025, the Acton Town Council observes that an individual claiming to be part of an organization called "Better World Group" had emailed select Acton residents to request "one on one" meetings to discuss how the BESS project can "align with" organization priorities. The Acton Town Council pointed out that "'One on one' meetings in backrooms with select individuals is not how authentic community engagement is done and it is certainly not how 'Community Benefit' Plans should be developed. To the contrary, such methods introduce furtiveness, create divisiveness, and engender distrust. A better path would be to convene a community meeting and invite community based organizations to discuss the issue openly to ensure all organizations hear the same message and have the same opportunity to provide initial input on the Benefit Plan" (page 2).

[45] SB 254 expands "Community Based Organizations" to include "Community Foundations".

ATTACHMENT 1

LETTER FROM THE AADUSD SUPERINTENDENT OF SCHOOLS.

Acton-Agua Dulce Unified School District

32248 Crown Valley Road | Acton, California 93510
(661) 269-0750 | Fax (661) 269-0849

Empowering Today's Learners to Thrive in Tomorrow's World

October 30, 2025

California Energy Commission
1516 Ninth Street
Sacramento, CA 95814

Subject: Correction of Inaccurate Student Enrollment Data Submitted for the BESS Prairie Song Reliability Project

Dear Commissioners,

On behalf of Acton Agua Dulce Unified School District, I am writing to bring to your attention an inaccuracy in the student enrollment data submitted to the California Energy Commission associated with the BESS Prairie Song Reliability Project. The report currently lists our district's enrollment as 12,875 students, which is incorrect.

Our actual district enrollment is 1,120 students. The figure of 12,875 appears to include the combined enrollment of several independent charter schools for which our district serves as the Local Educational Agency (LEA). While these charter schools are authorized under our oversight, they are independently operated entities with separate governance, administration, and facilities, also outside of our district boundaries. Their student enrollment should not be attributed to our district's direct operational population.

We respectfully request that this error be corrected in the Commission's records to reflect our verified district enrollment of 1,120 students.

Our district is committed to transparency and data accuracy. We are happy to provide any documentation or verification necessary to support this correction. Please contact my assistant, Mrs. McCauley at 661 269-0750 or ymccauley@aadusd.k12.ca.us should additional information be required.

Thank you for your prompt attention to this matter.

Sincerely,

Dr. Eric Sahakian
Superintendent
Acton-Agua Dulce Unified School District

cc:
Board President, Mr. Lester Mascon

ATTACHMENT 13

EXCERPT FROM SORT LETTER DATED AUGUST 18, 2025 ADDRESSING HAZARDOUS WASTE GENERATED BY THE BESS PROJECT.

The Application Ignores Significant Waste Management Impacts.
Section 3.14 addresses how the BESS Project will dispose of waste, and Table 3.14-1 lists four Class III landfills that are nearest to the project (although only three are operational because Chiquita Canyon is closed). The Application also identifies two hazardous waste disposal facilities that can accept hazardous waste generated by construction, operation, and decommissioning activities (Kettleman City and Buttonwillow). Notably, the activity that is likely to generate the largest waste stream is decommissioning; however, the Application does not address this waste stream other than to state on page 3.14-8 that decommissioning is "not expected to generate quantities of waste such that the surrounding accepting facilities cannot accommodate the additional materials". There is no evidence to support this claim because the Application does not quantify the amount of waste that will be generated from decommissioning. More importantly, Section 3.14 does not discuss (or even address) the measures that will be undertaken to recycle the thousands of BESS units that will be removed at the end of their lifecycle. In fact, the only mention of BESS disposal is in an offhand statement on page 3.14-8 that "Batteries and other equipment and materials will be recycled to the extent feasible to minimize disposal in landfills".

The developer is disinclined to even admit that spent BESS units are designated as hazardous waste because the Application states on page 3.14-7 that "batteries *may* be considered hazardous waste in California when they are discarded" (emphasis added). However, spent lithium batteries are banned from Class III landfills and at the very least, they are designated as hazardous waste by the California Department of Toxic Substance Control (DTSC) because they meet the definition of "Universal Waste"[1]. SORT has consulted with DTSC and understands that there are no licensed lithium battery recycling facilities in California, so the Kettleman City and Buttonwillow facilities identified in the Application are not equipped to process the enormous hazardous battery waste stream that will be generated by the BESS Project.

The "Decommissioning Plan" provides no information on how or where BESS units will be disposed of other than to say that "batteries would be recycled at a specialized recycling plant" and that adequate facilities will be available when needed because "recycling enhancements and innovation are anticipated to continue and are anticipated to be in place by the projected end of life of the proposed BESS, estimated to be approximately 40 years after the start of operations". However, the recycling facilities required to process BESS waste from the Project must be online within 10 years, not 40 years because LFPO BESS units only last about 10 years and then they must be replaced.

[1] https://dtsc.ca.gov/universalwaste/

Recycling of lithium batteries is a complicated and dangerous process;[2] in fact, the largest recycling facility in the U.S.A. burned down in Missouri just nine months ago (less than a year after it began operating); the facility operator appears to be linked to another lithium battery recycling facility in Illinois that experienced two large fires[3]. Lithium battery recycling is a young industry and recycling processes are still being perfected. Given the troubling dearth of existing and planned lithium battery recycling facilities and the fact that the BESS Project will begin generating a substantial volume of battery waste within 10 years of startup, SORT contends it would be imprudent for the Commission to proceed with licensing the BESS Project until a "Recycling Plan" is developed that clearly identifies which recycling facilities will receive and handle the thousands of battery units that will be soon be retired from the BESS Project. The Recycling Plan must demonstrate that the recycling facilities have sufficient capacity to process the entire hazardous waste stream and that this capacity is reserved exclusively for the BESS Project. The latter is particularly important: numerous BESS facilities have been constructed over the last 5 years, and there does not appear to be sufficient recycling capacity available to process the cumulatively significant hazardous waste streams that these projects will soon generate. The developer must demonstrate that the BESS Project will not exacerbate this looming waste disposal problem. The environmental impact analysis of the BESS Project must adopt a "cradle to grave" perspective which considers the public safety risks posed by the transportation of thousands of BESS units to and through Acton as well as the risks posed by operating these BESS units and ultimately transporting and recycling them at the end of their useful life.

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[2] NFPA Article "Missouri Fire Highlights Unique Dangers of Battery Recycling" found here: https://www.nfpa.org/news-blogs-and-articles/blogs/2024/11/01/missouri-battery-plant-fire

[3] https://fox2now.com/news/missouri/history-of-fires-for-linked-recycling-facilities/