Hazard Assessment of Battery Energy Storage Systems
By Ian Lines, Atkins Ltd

1 INTRODUCTION

1.1 Scope

HSENI is aware of the hazards associated with large scale lithium-ion Battery Energy Storage System (BESS) sites. Consideration has been given to whether such sites should come under the COMAH and Hazardous Substances Consent Regulations, and following discussions with COMAH colleagues in HSE and HSA the view is that batteries alone would not bring a facility under COMAH (as batteries are regarded as articles and not dangerous substances under CLP).

Nevertheless, HSENI is still interested in the consequences of a fire in a battery container unit as there may be a need for HSENI to provide advice to Local Planning Authorities, comment on an environmental assessment, provide advice to fire fighters or review an operator's own risk assessment.

HSENI is aware that this is a relatively new area, with little available guidance, and has therefore requested that Atkins provide some initial advice based on the following scope:

- Review of incidents involving lithium-ion battery energy storage sites (and manufacturing sites)
- Review of technical papers/information, concentrating on any information relevant to major accident hazards
- Consideration of fire load (associated with the electrolyte)
- Consideration of potential for flammable vapour explosion
- Assessment of HF dispersion toxic hazard ranges to DTL/IDLH using ADMS
- Brief consideration of washout/deposition from fire plumes
- Brief consideration of firewater run-off issue (environmental hazard)
- Summary of key issues

It is emphasised that this Technical Note is only intended to provide brief advice in most of the above areas, and that in some areas there is very little available good information. HSENI has indicated that their main concern is the firefighter who could be facing a fire at one of these facilities, and therefore their principal interest is in the potential toxic fire plume, and potential explosion, associated with a single BESS container. This Technical Note therefore concentrates on those areas.

It is recognised that this has been a rapidly developing area over the last few years, and so the information presented in this Technical Note would benefit from regular review.

1.2 Background

A recent issue of Energy Storage News (11 January 2021) summarises the key hazards for firefighters:

> *Energy storage is a relatively new technology to fire departments across the US. While different fire departments have differing levels of exposure to battery energy storage systems (or BESS for short), the primary concern of each is the same: the safety and well-being of their first responders.*
>
> *Departments and local officials are, however, becoming increasingly aware of the hazards associated with battery storage and it is important that their concerns be properly addressed. Addressing these concerns in a complete and transparent manner has been seen not only to promote overall first responder safety but also to ensure project success. Perhaps the most defining characteristic of lithium-ion battery failures is a state known as 'thermal runaway', in which a battery cell experiences uncontrollable overheating, often accompanied by the release of large quantities of flammable off-gases.*
>
> *Thermal propagation from the failing cell may lead to incipient thermal runaway of adjacent cells, thus creating a cascading failure across the system, resulting in tremendous amounts of heat and gas. When these gases are allowed to accumulate in an enclosed space (such as a BESS container), an explosive atmosphere may develop, which, given an ignition source, may lead to a devastating deflagration (explosion) event. This blast wave can cause damage to nearby buildings and structures, as well as first responders who may be arriving on the scene, as was seen in the incident that unfolded in Arizona in 2019. Deep-seated fires are also common in lithium-ion failure events. These fires are not easily extinguished and may continue for hours, fuelled by heat and gas from cascading cell failures. Even if*

suppressed by water, stranded energy within the cells often causes reignitions, thus perpetuating the event.

Concerns based on environmental risks are also often cited by fire departments across the country. Large quantities of smoke and gas are often released during battery fires, with high levels of carbon monoxide and hydrogen cyanide measured on-site in Arizona at the time of the incident. Contaminated runoff water may also affect the surrounding area. Electrical hazards also exist during and after battery failure events and should not be overlooked.

2 REVIEW OF INCIDENTS

This section provides a brief review of incidents involving lithium-ion cells, and key lessons learned in terms of major hazard assessment. It is not intended to be comprehensive, but highlights important events such as the 2019 McMicken (Arizona) BESS explosion.

2.1 Incidents Involving Single Cells

Many billions of individual lithium-ion cells have been produced worldwide over the last 30 years, and there have been thousands of incidents which have been potentially hazardous. Many of these have been well reported in the press, and some have led to major product recalls. The majority of these incidents relate to Thermal Runaway (TR) events due to a short circuit within a cell between the anode and cathode. Such events are often apparently spontaneous and the precise cause of the short circuit is often not clear. Common causes can include:

- Impact/vibration/penetration
- Manufacturing defect
- Failure of the battery management system
- Overheating
- Overcharging
- Undercharging

It is also noted that as the widespread use of such cells has grown very rapidly, there is relatively little data on incidents that may be related to aging for current cell designs.

Incidents are generally most severe when a cell has a high State of Charge (SOC). Any major failure of a charged cell can lead to the rapid and energetic ejection of the electrolyte liquid, as a short (e.g. 1 to 2 m long) jet flame. It is noted that such failure events with charged cells are highly likely to ignite, but there are also situations where cascading thermal runaway can occur due to heat transfer between cells without any ignition, due to the highly exothermic nature of the thermal runaway.

The precise nature of an incident may depend on the cell size and whether the cell is cylindrical, pouch or prismatic. Large pouch cells are generally used in large scale BESS container units.

2.2 Incidents at BESS Facilities

Table 2-1 lists a number of incidents which have occurred at BESS facilities.

Table 2-1 Incidents at BESS Facilities

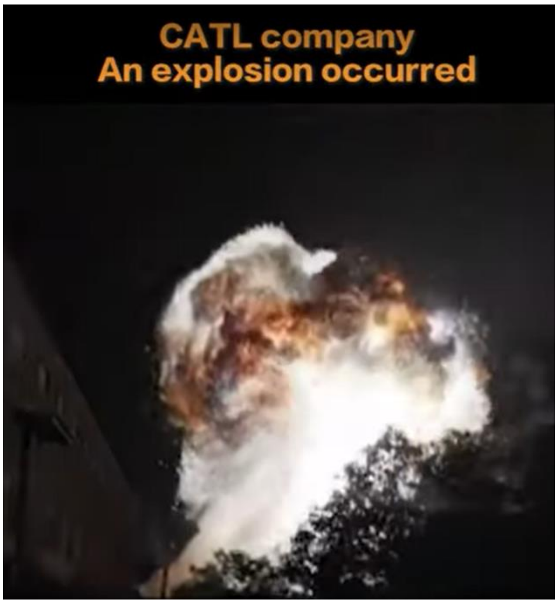
Location (Company)	Date of Incident	Description of Incident
Arizona, USA (Arizona Public Service Company)	Nov 2012	In November of 2012, a fire occurred at a state-of-the-art solar energy storage system that the Arizona Public Service Company (APS) was testing. The system, the relative size of a shipping container with a capacity of 1.5 MW, had been running since February of 2012. Similar to the First Wind fires, the fire department personnel allowed the fire to burn freely for some time. The cause of the fire was not reported. Ref. Blum and Long (2016)
Unknown	2014	A fire in a Li-ion battery storage unit caused an explosion that seriously injured fire fighters. Ref. Ronken (2017)
Yeongju, South Korea	Nov 2018	Fire at lithium-ion PV power plant. Ref. INERIS (2021)
Cheonan, South Korea	Nov 2018	Fire at lithium-ion PV power plant. Ref. INERIS (2021)
Geochang South Korea	Nov 2018	Fire at lithium-ion PV power plant. Ref. INERIS (2021)
Munyeong, South Korea	Nov 2018	Fire at lithium-ion PV power plant. Ref. INERIS (2021)

Location (Company)	**Date of Incident**	**Description of Incident**
South Korea Jecheon	Dec 2018	Fire at lithium-ion peak load reduction plant. Ref. INERIS (2021)
Samcheok, South Korea	Dec 2018	Fire at lithium-ion PV power plant. Ref. INERIS (2021)
Yangsan, South Korea	Jan 2019	Fire at lithium-ion peak load reduction plant. Ref. INERIS (2021)
Wando, South Korea	Jan 2019	Fire at lithium-ion PV power plant. Ref. INERIS (2021)
Jangsu, South Korea	Jan 2019	Fire at lithium-ion PV power plant. Ref. INERIS (2021)
Ulsan, South Korea	Jan 2019	Fire at lithium-ion peak load reduction plant. Ref. INERIS (2021)
Chligok, South Korea	May 2019	Fire at lithium-ion PV power plant. Ref. INERIS (2021)
McMicken Substation, Surprise, West Valley, Arizona, USA (Arizona Public Services)	19/4/2019	The incident occurred at two twinned grid-scale energy storage systems of 2 MW / 2 MWh at the McMicken substation. The explosion caused a “significant pressure wave” resulting in the injuries of four firefighters. Technical analysis by certification and standards group DNV GL indicated that the event had begun with internal cell failure in a single LG Chem 0.24 kWh pouch cell in the ESS. The fire suppression system onsite worked as designed, but it was inadequate to prevent or stop the cascading thermal runaway. Heat transfer between the cells in a module, and then between modules, in one of the battery racks caused the thermal runaway to propagate - facilitated by the absence of “adequate thermal barrier protections between battery cells,” which could have stopped or slowed the propagation. Whilst the incident was at first thought to be a fire, it was in fact a cascading thermal runaway from a single cell, through every other cell in the module, and then through all the modules in Rack 15 via heat transfer. It took around two hours from the first report of a suspected fire at the facility, at 17:48 local time on 19 April 2019, to around 20:04 before an explosion happened from inside the BESS. The BESS and its container were “essentially destroyed” and the incident left several firefighters injured. On the day of the incident, the BESS was performing solar smoothing applications - charging during the daytime from local solar generation and discharging electricity to the grid during the evening peak load. Data collected by APS found that just before 5pm on 19 April, there was a sudden drop in voltage during one of the system’s charge cycles. Thermal runaway began shortly after that. Smoke detection systems went into operation but off-gassing of battery cells as the thermal runaway cascaded through neighbouring modules caused a “flammable atmosphere within the BESS,” the DNV GL report said. Then, when firefighters opened the side container door around three hours after thermal runaway began, an explosion occurred within 2-3 minutes, causing the side and rear doors of the BESS as well as other debris to be ejected by the explosion. It is thought that opening the doors agitated flammable gases that remained and brought the gases into contact with a spark or heat source - causing the explosion. Ref. McKinnon, DeCrane and Kerber (2020) – Detailed incident report. DNV GL (2020) – Technical incident report. Energy Storage News (23 April 2019, 29 July 2020, 12 March 2021, 25 March 2021)

Location (Company)	Date of Incident	Description of Incident
Carnegie Road, Liverpool, England (Ørsted) See Figure 2.1	15/9/2020	Large grid battery system container fire at 20 MW BESS site which lasted several hours. Merseyside Fire & Rescue Service, local first-responders, said that crews were alerted shortly before 1am on 15 September and arrived to find a “large grid battery system container well alight”. A "massive bang" was heard as fire crews rushed to tackle the blaze. One resident said he "heard an explosion after midnight" while another said their house "shook”. Five fire engines were immediately on the scene after being alerted at 12.52am to reports of a blaze on Carnegie Road in Tuebrook. The fire service said that it had used main jets and ground monitors in tackling the fire, asking residents nearby to keep their windows and doors closed due to smoke from the incident. The blaze went on for several hours, with an update from the service at 7:30am noting that although operations at the site had been scaled down, firefighting was ongoing, with two ground monitor units and a main water jet still in use. A further update at 11:45am said one fire engine was still at the scene, with firefighting still continuing, although by that stage only one hand-held pump was in use. It was reported that the explosion caused a “significant pressure wave”, causing debris to be thrown between 6 and 20 metres away according to the fire department’s response report. The environmental impact from firewater runoff was also a major concern. Ref. Energy Storage News (16 September 2020 and 25 March 2021) • Fire at 20MW UK battery storage plant in Liverpool - Energy Storage Virtual Summit [redacted]
Ningxiang, Hunan Province, China (CATL Brunp Recycling Technology plant) See Figure 2.2	7/1/2021	Explosion and fire occurred at one of the old workshops of the battery recycling plant - 1 person was killed and 6 were seriously injured. CATL is a battery supplier to Tesla. • [redacted] • #177 Explosion at CATL-owned company #shorts - YouTube

Figure 2.1 Incident at Carnegie Road, Liverpool (15/9/2020)

Figure 2.2 Incident at Ningxiang, Hunan Province, China (7/1/2021)



It is noted that there have been many incidents in Asia relating to BESS facilities, but details are generally scarce or unavailable.

2.3 Incidents at Battery Manufacturing Facilities

Table 2-2 lists a number of incidents which have occurred at battery manufacturing facilities.

Table 2-2 Incidents at Battery Manufacturing Facilities

Location (Company)	Date of Incident	Description of Incident
Koriyama City, Japan	4/11/1995	An explosion occurred at a Sony battery factory in Koriyama City, Japan, where cylindrical lithium-ion batteries for notebook PCs were manufactured. The fire occurred on the floor where batteries underwent final testing. Cells in this location were stored in racks 4-high under ambient temperature conditions. Ultimately, approximately 3 million cells burned, 7,000 m^2 of facility was damaged and two people were injured. Ref. Mikolajczak et al (2011)
Moriguchi, Osaka, Japan (Matsushita Battery Industry Factory)	Aug 1997	An explosion occurred at the Matsushita Battery Industry factory in Moriguchi, Osaka. The owner of the factory, T&T Dream, was a subcontractor for Matsushita. The factory carried out charge/discharge and check processes of cylindrical lithium-ion batteries. Cells in this location were stored on thirteen layers under ambient temperature conditions. Ultimately, approximately 1.22 million cells burned, 1,700 m^2 of facility was burned, buildings within a 175 m radius were damaged, and two people were injured. Ref. Mikolajczak et al (2011)
Karlstein, Germany (BMZ)	Aug 2008	A fire occurred at Batterie-Montage-Zentrum (BMZ) in Karlstein, Germany. The fire destroyed a production area and a warehouse. Ref. Mikolajczak et al (2011)
Pawcatuck, Connecticut, USA (Yardley Technical Products)	Sep 2008	A large format lithium-ion battery that was undergoing testing at Yardney Technical Products in Pawcatuck Connecticut caught fire. Ref. Mikolajczak et al (2011)
Dongguan City, China	2014	Fire in a lithium-ion battery factory in Dongguan City in China, which caused 5 deaths and 6 injuries. Ref. Niu and Li (2018)
China (Samsung SDI battery manufacturing facility)	8/2/2017	The fire occurred in the battery waste area of the factory, after faulty lithium-ion batteries went up in flames. • [redacted]
North Phoenix, Arizona, USA (Gruber Motor Company)	6/5/2017	Pallet of Li batteries caught fire and 5 minutes later the whole building was burning, producing toxic smoke which spread all over the north valley and forced evacuation of nearby buildings. • Fire breaks out at factory that produces lithium batteries - Bing video
Peera Garhi, New Delhi India See Figure 2.3	2/1/2020	Battery factory collapses after explosion in fire during firefighting operations – killing 1 and injuring 19 other firefighters. • Battery Factory In Peeragarhi Collapses During Fire Fighting Operations | CNN News18 [redacted] • Battery factory collapses in fire in New Delhi, killing 1 [redacted]

Figure 2.3 Incident at Peera Garhi, New Delhi, India (2/1/2020)

The incidents in Table 2-2 show that major incidents at battery manufacturing facilities are most likely to occur in the Formation, Aging and Testing stage, where large numbers of cells are being charged for the first time. Such events are less likely at BESS sites as the cells have been through all the necessary testing, but the nature of the potential incidents is similar due to the large number of cells present.

2.4 Other Incidents

Table 2-3 lists a number of incidents which have occurred at other facilities.

Table 2-3 Incidents at Other Facilities

Location (Company)	Date of Incident	Description of Incident
Germany	2017	A major fire broke out in a bicycle warehouse in Germany that also contained a large number of electric bicycles with Li-ion batteries. It proved an extraordinary challenge for the fire brigade and ultimately resulted in a total loss in the warehouse. Four employees suffered minor injuries. Ref. Ronken (2017) • [redacted]
Lyons Park industrial estate, Coventry, England	20/2/2020	Factory storing Li batteries goes up in flames. • Factory where lithium batteries stored goes up in flames - CoventryLive [redacted]

Mikolajczak et al (2011) also lists a number of air transport incidents involving lithium-ion batteries.

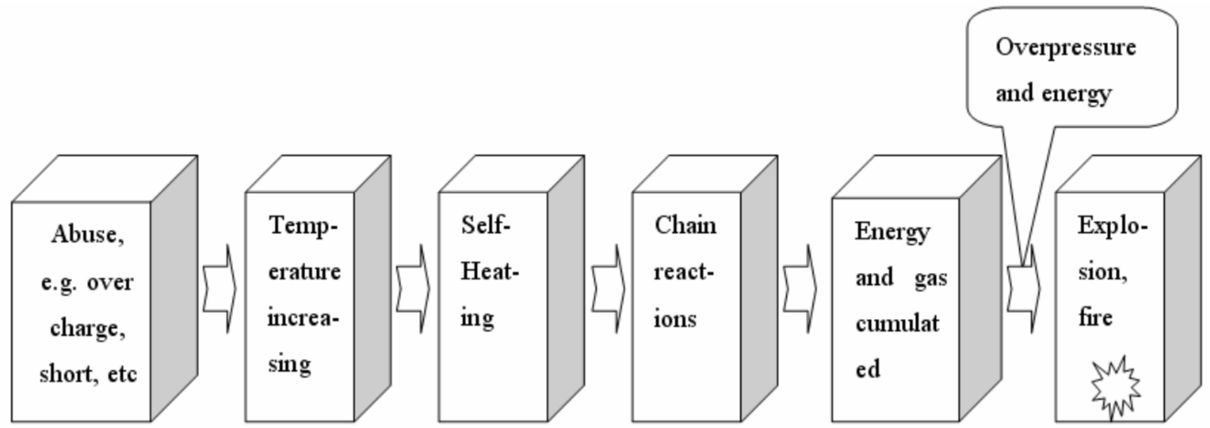
3 REVIEW OF LITERATURE

This section presents a brief literature review concentrating on information which is relevant in terms of major hazard safety issues.

3.1 Published Papers and Reports

Wang, Sun & Chu (2005) provide an overview of how lithium-ion cells can fail, leading to fire and explosion.

Figure 3.1 Development of Cell Failure (Wang, Sun & Chu, 2005)



Ditch and de Vries (2013) and **Ditch (2014)** describe a detailed study of the flammability characterisation of lithium-ion batteries in bulk storage, which tested the effectiveness of sprinklers and measured heat release rates etc. The overall goal was to develop sprinkler protection recommendations for bulk storage of Li-ion batteries. The test results show that fires can develop rapidly, reaching heat release rates of several MW for a single pallet of batteries.

Mikolajczak et al (2011) present a literature review of battery technology, failure modes and events, usage, codes and standards, and a hazard assessment during the life cycle of storage and distribution. The failure modes and root causes are discussed, together with information on flammable cell components and the fire behaviour of cells and battery packs. Key gaps in knowledge, such as the vent gas composition, are identified.

Blum and Long (2016) summarise a literature review and gap analysis related to Li-ion battery ESSs, as well as full-scale fire testing of a 100 kWh Li-ion battery ESS. The overall objective was to help enable the development of safe installation requirements and appropriate emergency response tactics.

Larsson, Andersson, Blomqvist and Mellander (2017) provide a useful study of toxic fluoride emissions from lithium-ion battery fires. It is shown that lithium-ion battery fires generate intense heat and considerable amounts of gas and smoke. It is noted that although the emission of toxic gases can be a larger threat than the heat, the knowledge of such emissions is limited. The paper presents quantitative measurements of heat release and fluoride gas emissions during battery fires for seven different types of commercial lithium-ion batteries. The results are validated using two independent measurement techniques and show that large amounts of hydrogen fluoride (HF) may be generated, ranging between 20 and 200 mg/Wh of nominal battery energy capacity. In addition, 15 to 22 mg/Wh of another potentially toxic gas, phosphoryl fluoride (POF_3), was measured in some of the fire tests. Gas emissions when using water mist as an extinguishing agent were also investigated. It is concluded that fluoride gas emission can pose a serious toxic threat and the results are crucial findings for risk assessment and management, especially for large Li-ion battery packs. The paper states that:

> *If extrapolated for large battery packs the amounts would be 2–20 kg for a 100 kWh battery system, e.g. an electric vehicle and 20–200 kg for a 1000 kWh battery system, e.g. a small stationary energy storage. The immediate dangerous to life or health (IDLH) level for HF is 0.025 g/m^3 (30 ppm) and the lethal 10 minutes HF toxicity value (AEGL-3) is 0.0139 g/m^3 (170 ppm). The release of hydrogen fluoride from a Li-ion battery fire can therefore be a severe risk and an even greater risk in confined or semi-confined spaces.*

Ronken (2017) also describes the risks and safety measures required for lithium-ion batteries, and emphasises the importance of a suitable risk assessment. Several incidents are also identified (see Section 2.2).

Niu and Li (2018) describe a fire risk assessment method for use in lithium-ion battery factories, and summarise the key areas where fire risks are significant, based on experience with such facilities in China. It is suggested that in the event of a short circuit, lithium can react with the various electrolyte components (ethylene carbonate, propylene carbonate, dimethyl carbonate) to form flammable gases such as propene (C_3H_6). A risk matrix is used to assess all stages of the battery manufacturing process. Several events are identified as likely to result in severe injury, but none are identified as likely to result in death. Serious events such as the spontaneous ignition of batteries in storage are identified as unlikely to happen in a lifetime.

Finegan et al (2019) describe detailed experiments where internal short circuits (ISCs) were caused in cylindrical 18650 cells. These ISCs cause the Li-ion battery to fail catastrophically due to thermal runaway. That is, at a critical temperature and in the presence of non-aqueous liquid electrolytes and oxygen, the active materials within a Li-ion battery can exothermically react. Exothermic reactions can become self-sustaining when local heat generation is greater than heat dissipation, resulting in violent combustion and total cell failure. During thermal runaway, it is estimated that about 2 litres of gas is generated per amp hour (Ah) of commercial $LiFePO_4$ and $LiNi_xCo_yAl_zO_2$ 18650 cells. It is noted that modern 18650 cells have capacities greater than 3 Ah, and can generate more than 6 litres of gas within about 2 seconds during thermal runaway, which is mostly flammable. In this short time (< 2 seconds), more than 70 kJ of heat can also be generated.

The Department for Business, Energy & Industrial Strategy (BEIS, 2020) reviewed the safety risks associated with domestic battery energy storage systems. The authors state that even though few incidents with domestic battery energy storage systems (BESSs) are known in the public domain, the use of large batteries in the domestic environment represents a safety hazard. Three hazard categories are identified:

- Excessive heat generated deep inside a battery pack as cells fail and thermal runaway propagates through the pack, highlights the need to design packs to minimize risk for propagation and limit spread of fire between cells/modules. Early detection and means for cooling individual cells as they begin to fail are important for avoiding thermal runaway of the full system.
- Cell and pack failures can generate large volumes of gases resulting from the rapid pressure build-up and vent release as the system heats up. Management of gases generated must be considered in pack and system design.
- The toxicity of gases generated from battery fires may require specific consideration in the design of ventilation systems.

Key considerations regarding risk mitigation are summarised as:

- The Battery Management System (BMS) has a central role in keeping cells within their operating window for voltage, current and temperature. BESS safety standards have specific requirements and tests which apply for the BMS.
- Internal cell faults, though rare, do occur. For well-constructed 18650 cells, the failure rate from an internal event is estimated as one in ten million (0.1 ppm). This translates to a single cell failure in every 10,000 BESS (assuming a 5 kWh BESS containing 500 18650 cells). This is not to say that 1 in 10,000 BESSs will fail, with significant risk of fire. Proper BESS design and construction should be capable of preventing propagation of cell failure across the battery pack. A single cell failure should be controllable.
- If the system is well designed, it should take into consideration propagation of a thermal event arising from a single cell. This is of great importance for the risk mitigation and will have a large impact on the overall risk assessment for the system. Control of single cell failures within a pack reduces the risk of complete system failure and residential fire. Assessment of cell failure propagation is captured in the standards applicable for domestic lithium-ion battery storage systems such as BS EN 62619 and IEC 62933-5-2.

The BEIS report also provides some statistics for the likelihood of failures, although it doesn't deal with large scale BESS installations. Hydrogen fluoride, CO and CO_2 are all identified as potential toxic combustion products following a thermal runaway. The potential for an explosion is also mentioned, either as a result of a cell failing violently due to an internal build-up of pressure, or as a result of ignition of flammable gases released from a cell. The total heat released during total combustion of lithium-ion batteries ranges from 30 to 50 kJ/Wh, or 4 to 10 MJ/kg, which is about 5-10 times less than for organic materials like plastic or paper. No projectiles were observed in any full scale testing of larger racks of batteries for energy storage systems. The violence of thermal runaway, and the gas volume generated, tends to increase with SOC.

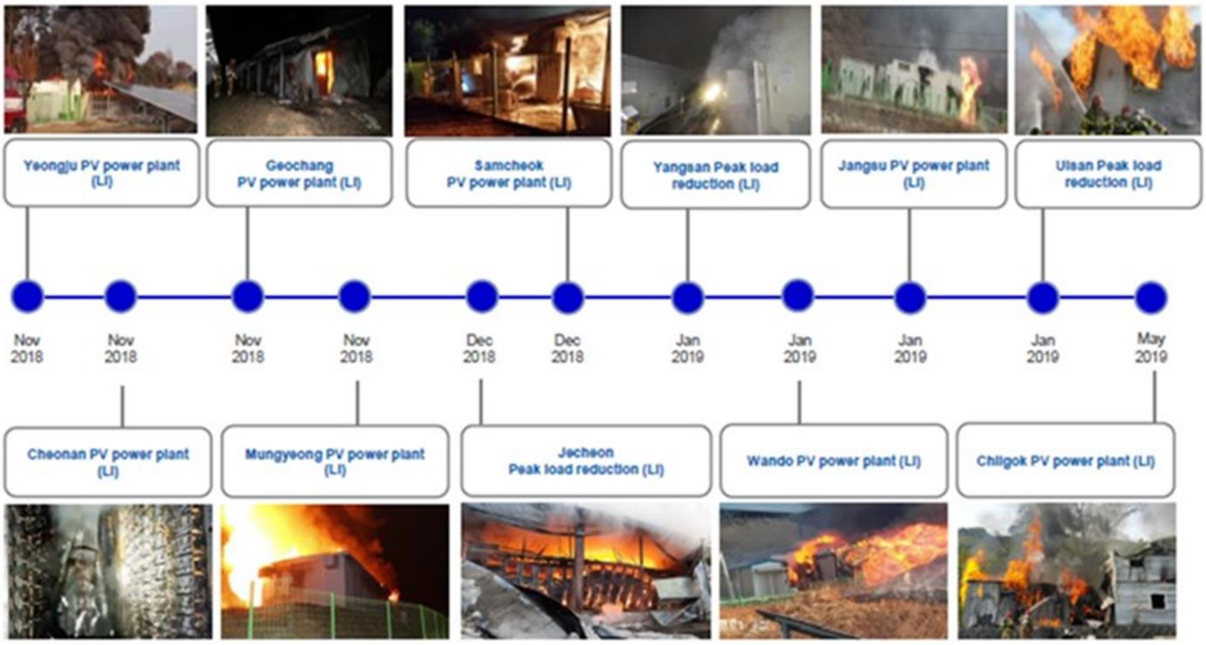
The BEIS report discusses the vent gases that can be generated, including volatile organic compounds (such as alkylcarbonates, methane, ethylene and ethane), hydrogen, carbon monoxide, carbon dioxide, soot and other particulates containing nickel, cobalt, lithium, aluminium, copper. The authors note that a major point of discussion is the amount of HF and other fluorinated compounds found in vent gases, because of their toxicity, and that this is still an open question. Some tests have indicated HF concentrations well in excess of 100 ppm.

Diaz et al (2020) provide a comprehensive review of fire safety information for lithium-ion batteries. The authors note that the majority of research has considered single cells, and there is much less safety information relating to larger scale fires involving pack, modules, or large numbers of cells. The review includes information on the various challenges faced by the industry, including detection and reliability issues and emergency response challenges. The use of water for fire fighting appears to be preferred, although there are still issues with reignition.

Rosewater et al (2020) presents a systematic hazard analysis of a hypothetical, grid scale lithium-ion battery powerplant to produce sociotechnical 'design objectives' for system safety. This includes key considerations for firefighter training objectives.

INERIS (March 2021) recently presented an overview of the lithium-ion cell assessments and modelling that they are currently undertaking in France. The presentation included brief details of fires at large scale energy storage sites in South Korea, as illustrated in Figure 3.2.

Figure 3.2 Examples of Fires at BESS Sites in South Korea (INERIS, 2021)



It was concluded that there was no single root cause for these events.

INERIS noted that there have been similar fires in Belgium, UK, France, US (Arizona) and Australia. A number of issues and uncertainties were identified in relation to fire protection and firefighting for such sites:

- Fixed fire fighting systems: water (sprinklers, water mist)?, Foam?, Inert gas?, Others?
- Fire fighter capacities for such a fire: drowning a battery container in water is not really an option
- Safety aspect of emergency response: gas toxicity and explosivity

One conclusion from their presentation was that the toxic combustion products from a small fire involving a lithium-ion battery are generally not significantly more hazardous than a comparable sized fire with packaging and plastics etc. However, for a large fire involving many lithium-ion cells, the view expressed was that the HF vapour was the most significant toxic concern.

3.2 Project Specific References

HSENI has provided several documents which relate to BESS sites. These are considered briefly below in terms of the key data which is relevant in terms of the assessment of major hazards.

Haigh (2020) provides an analysis of what might occur under a loss of control scenario at the Kells BESS and what chemical reactions might take place. The site is described as having a total energy capacity of 26.3 MWh with:

25 ISO containers
28 racks in each ISO container
6 modules in each rack
22 lithium-ion cells in each module

The total quantity of electrolyte on site is 28.6 tonnes, together with 9.5 tonnes of polyvinylidene difluoride, all of which may generate HF in a fire. A fire involving a single container is predicted to generate 20 to 210 kg of HF. This corresponds to 19 to 200 mg/Wh, consistent with the range suggested by Larsson et al (2017).

Marks (2020) provides technical details for the Newry Energy Storage Ltd BESS located approximately 85 m North of No. 68 Cloghanramer Road, Newry, BT34 1QG. The site is described as having a total energy capacity of 18.635 MWh with:

5 ISO containers (3,727,000 Wh for each ISO container)
10 racks in each ISO container (372,700 Wh for each rack)
26 modules in each rack (14,336 Wh for each module)
16 lithium iron phosphate (LFP) cells in each module (896 Wh for each cell)

Each of the 20,800 cells on site, each with a mass of 5.46 kg, includes:

540 g of polyvinylidenefluoride-hexafluoropropylene copolymer (PVDF-HFP)
486 g of ethylene carbonate
432 g of dimethyl carbonate
432 g of propylene carbonate
378 g of diethyl carbonate
378 g of ethyl methyl carbonate
162 g of lithium hexafluorophosphate ($LiPF_6$)

It is predicted that a full stoichiometric decomposition of $LiPF_6$ will generate 4 moles of HF (plus other fluorine compounds). This corresponds to 354.2 kg of HF per ISO container. Similarly, a full stoichiometric decomposition of the PVDF-HFP would generate 1,679 kg of HF. Marks states that these stoichiometric results are considered worst case, and a more foreseeable prediction is based on the work of Larsson et al (2017) (i.e. 200 mg/Wh) giving 738 kg of HF per ISO container.

3.3 Standards

Standards for energy storage systems include:

NFPA 855 - Standard for the Installation of Stationary Energy Storage Systems, 2020
This debut edition addresses the dangers of toxic and flammable gases, stranded energy, and increased fire intensity associated with BESS sites. It is designed to give first responders and those who design, build, maintain, and inspect facilities the information they need to prepare for ESS safety.

IEC 62619 - Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries, for use in industrial applications, 2017
Specifies requirements and tests for the safe operation of secondary lithium cells and batteries used in industrial applications including stationary applications.

There are obviously many other standards which are important, but the above are some of the most directly relevant. NFPA 855 is one of the most useful in terms of major hazard and firefighting considerations.

4 CONSIDERATION OF FIRE LOAD

The main fire load within a BESS container is the electrolyte within each cell. The precise composition of the electrolyte generally involves several flammable liquids and lithium hexaflurophosphate, as detailed in Section 3.2 by Marks (2020).

The overall heat of combustion of the electrolyte is approximately 20,000 kJ/kg.

Electrolyte typically makes up about 40% of the mass of a cell in a BESS. For other cell designs, such as cylinder cells, it is typically closer to 15% of the mass.

Any fire is likely to start as a result of failure of a single cell, which then escalates by involving progressively more cells. In the very early stages, the fire may not be ventilation controlled, but the container would rapidly begin to fill with combustion products, and the fire would become ventilation controlled. If the container becomes breached then the fire will no longer be ventilation controlled.

The growth of the fire is therefore likely to be similar to fire growth in other situations, such as a warehouse fire, although the rate of fire growth is likely to be higher due to the exothermic nature of the thermal runaway event.

For the purposes of assessing the fire, a conservative assumption typically adopted by the HSE is that the entire contents are combusted over a relatively short period of 30 minutes (Atkinson and Briggs, 2019). This assumption can be useful for defining a heat release rate and maximum source term for toxic combustion products, but it is noted that in reality such fires could continue to burn for many hours. Lithium-ion fires are also well known for re-igniting after having been apparently extinguished.

5 POTENTIAL FOR EXPLOSION

The potential for explosion during the course of a major incident in a BESS ISO container is an important issue which has recently become better understood following several incidents.

It is well known that individual cells may fail explosively due to the build-up of pressure within the cell, but this will depend on the cell design. Pouch cells tend to fail easily on seams, and so, considered individually, may be less likely to explode than, for example, cylinder cells. However, when pouch cells are packed into a module it may be more difficult for gases to vent, and so an explosion may still be possible. The energy of such an explosion would depend on the module design. Such an event could produce a loud bang as the module fails, but the event is likely to be contained within the ISO container.

More significantly, it is also known that cell failures can generate quantities of flammable vapour. If a 10 Wh 18650 cell can generate 6 litres of gas (Finegan et al, 2019), an 896 Wh pouch cell could theoretically generate over 500 litres of flammable vapour. Several such failures could occur before the vapour ignites. Suppression systems can prevent flaming, though flammable vent gases can continue to be released due to cascading thermal runaway as a result of heat transfer between cells and modules. Ignition can then lead to a vapour cloud explosion (VCE) within the ISO container. The worst case is if such flammable vapour fills the entire ISO container (typical dimensions are 40 x 8 x 8.5 feet, or 77 m^3). It is noted that the 2019 McMicken incident only involved thermal runaway of the cells in a single rack, and this was still sufficient to generate enough flammable gas for a significant explosion.

Table 5-1 provides hazard ranges to various levels of overpressure for hydrocarbon vapour cloud volumes of 0.5, 5 and 50 m^3, based on a standard analysis using the TNO Multi-Energy Model with a typical ignition strength of 7 (based on the type of approach typically adopted by HSEGB for VCEs).

Table 5-1 Distances to Various Levels of Explosion Overpressure

Volume of vapour involved (m^3)	**0.5 m^3**	**5 m^3**	**50 m^3**
	Distance (m) to various levels of overpressure		
600 mbar	2	5	10
300 mbar	3	7	16
140 mbar	6	12	26
70 mbar	10	21	45

Any flammable vapours released from cells may be ignited almost immediately, without any generation of overpressure, but there have been several incidents where explosions have been reported in containers. This delayed ignition of vapour can occur if a fire suppression system prevents flaming. Continued release of vent gases from failed cells after the suppression system operates can then lead to a build-up of flammable gas, which can then ignite leading to an explosion. There have also been incidents with no suppression system where a build-up of flammable gas has occurred without a fire, until delayed ignition caused an explosion.

It is noted that HSEGB typically use 600, 140 and 70 mbar as the basis for defining the Inner, Middle and Outer land use planning zones for explosion hazards.

Table 5-2 provides some data from HSE (2005) on the effect on structures of various levels of blast overpressure.

Table 5-2 Effect of Various Levels of Explosion Overpressure

Damage Description	Incident Peak Side-On Overpressure (mbar)
General effects on buildings	
5% of exposed glass panes broken	1-3
50% of exposed glass panes broken	6-13
Near 100% of exposed glass panes broken	50-110
Limited minor structural damage	20-30
Doors and window frames may be blown in	50-90
Partial demolition of houses - rendered uninhabitable	70
Lower limit of serious structural damage	140
Partial collapse of walls and roofs of houses	140
Nearly complete destruction of houses	340-480
Probable total destruction of houses	690
Effects on UK brick built houses	
Category A damage (completely demolished)	690-1830
Category B damage (badly damaged and beyond repair)	240-590
Category Cb damage (uninhabitable without extensive repairs)	140-240
Category Ca damage (uninhabitable but repairable)	70-120
Category D damage (inhabitable but repairs required)	20-50
50% destruction of brickwork	280-480
Effects on plant	
Reinforced structures distort and unpressurised storage tanks fail	210-340
Wagons and plant items overturned	340-480
Extensive damage	>480
Failure of a pressurised storage sphere	>700

A recent Energy Storage News (25 March 2021a) focussed on the potential explosion issue at BESS sites, stating:

> *The challenges of explosion prevention – with flammable gases needing to be vented "very rapidly" – in the event of a battery fire have been highlighted at this week's Energy Storage Summit USA.*
>
> *Speaking at the event, hosted by our publisher Solar Media, Matthew Paiss, technical advisor, battery materials & systems at Pacific Northwest National Laboratory (PNNL), referenced the two most recent high-profile battery fires, with one at utility Arizona Public Services's (APS) energy storage facility in 2019 and one at Ørsted's 20 MW project in Liverpool, England in 2020.*
>
> *Both explosions caused a "significant pressure wave", with the APS incident resulting in the injuries of four firefighters and the Liverpool incident causing debris to be thrown between six and 20 meters away according to the fire department's response report.*
>
> *Paiss explained that there are "many similar battery enclosures operating today that could experience the exact same kind of failure".*
>
> *He said that most systems being deployed today do include a deflagration vent – which is used to vent gases after deflagration occurs – but "what is not very common in systems is deflagration prevention" which he described as typically being a mechanical exhaust system.*

It was also stated (Energy Storage News, 25 March 2021b) that:

> *Per Onnerud … said that statistically, some failures will always happen.*
>
> *While some experts have said that failure may only occur in one of every 10 million battery cells, energy storage projects are getting larger and contain more cells. Meanwhile the cells themselves are individually getting larger and therefore produce more gas if active materials like electrolyte catch fire.*
>
> *Explosions caused by that gas and fires caused by propagation should not be acceptable, Onnerud said. Battery design should be such that failures should be prepared for, and so that those failures can be dealt with "elegantly".*

The incident report for the 2019 McMicken Arizona incident (McKinnon, DeCrane and Kerber, 2020) provides photos which show that, when the fire service arrived, there was a low level cloud of vapour around the container (possibly associated with the suppression system), as shown in Figure 5.1.

Figure 5.1 Photos of ESS Prior to Explosion (McKinnon, DeCrane and Kerber, 2020)

When firefighters were satisfied that HCN and CO concentration had dissipated sufficiently, they proceeded to open the container door. The report describes what then happened to the four firefighters, stating:

> *At the moment of the deflagration event, the firefighters outside the hot zone described hearing a loud noise and seeing a jet of flame that extended at least 75 ft outward and an estimated 20 ft vertically from the southeast-facing door. In the event, E193 Capt and E193 FE were ballistically propelled against and under the chain-link fence that surrounded the ESS. E193 Capt came to rest approximately 73 ft from the opened door beneath a bush that had ignited in the event. E193 FE came to rest approximately 30 ft from the opened door. HM193 FF1 was projected toward the transformer and distribution box to the east of the ESS and remained within the fenced area. The entire HAZMAT team lost consciousness in the deflagration event. The event also dislodged or removed the SCBA face pieces and helmets from all of the HAZMAT team members.*

6 ASSESSMENT OF TOXIC FIRE PLUME

The literature is clear that a wide range of toxic combustion products could be generated in a fire. However, there seems to be reasonable agreement that for a major fire the most significant in terms of toxicity is hydrogen fluoride.

The quantity of HF generated can be estimated based on stoichiometric decomposition, or on experimental data. The approach of Larsson et al (2017), who suggest 20 to 200 mg/Wh based on experimental data, seems to be the most widely adopted approach, and use of the upper bound is likely to provide a cautious best estimate. For a fire involving an entire 5 MWh ISO container (i.e. slightly more than the 3.7 MWh ISO containers at Newry) this would correspond to 1,000 kg of HF.

The duration of the release is conservatively taken to be 30 minutes, which is consistent with the approach recommended by Atkinson and Briggs (2019) for warehouse fires. This implies a release rate of 0.56 kg/s. It is emphasised that in reality there would not be a constant release rate for 30 minutes, but it would grow exponentially to a maximum before gradually decaying over much longer than 30 minutes. However, it is noted that the HSE SLOT and SLOD are based on integrated dose, and so the precise time variation is not important for such criteria.

The other key factor in any toxic fire plume dispersion assessment is the buoyancy of the fire plume, as defined by the convective heat content of the fire plume. The major source of any heat release is likely to be the electrolyte, of which there could be up to about 10 tonnes in a single ISO container. Based on a typical heat of combustion of 20 MJ/kg for the electrolyte, and a release duration of 30 minutes, this would correspond to about 100 MW. In practice, combustion would not be complete and only a fraction would become convective heat in the fire plume (see below). It is noted that BEIS (2020) indicated a heat release of 30 to 50 kJ/Wh, which would correspond to 83 to 138 MW over 1800 seconds for a 5 MWh facility, which is reasonably consistent with the value of 100 MW.

Any generation of HF which is released from the ISO container will be advected downwind, though the plume will tend to rise due to the buoyancy of the hot fire plume. The container may also entrain some or all of the fire plume into its downwind wake, which may spread the plume out and bring it down to ground level, depending primarily on the wind speed.

The dispersion of a fire plume depends principally on the wind speed. At low wind speeds, a fire plume tends to rise buoyantly (see Figure 2.1) and ground level concentrations tend not to be significant. At higher wind speeds, there is generally more dilution of the plume, but it may not lift off the ground, and so moderate to high wind speeds generally represent the worst case for such fire plumes. A range of weather conditions has therefore been considered, namely D2, D5, D10 and F2. It is noted that atmospheric stability may also have some effect, and so stable F2 conditions have also been considered, although (unlike many toxic gas assessments) it is not expected that F2 will be the worst case in terms of hazard ranges.

As noted above, the heat content of the fire plume is a key parameter in determining the degree of buoyant plume rise - a higher heat flux leads to greater plume rise and lower ground level concentrations. Based on CERC (2018), the heat flux is typically calculated as:

$$F_b = (1 - \alpha_r)\, \varepsilon\, H_c\, m$$

Where F_b = Heat flux (W)
α_r = Fraction of heat radiated (typically 0.3)
ε = Efficiency of combustion (taken as 0.5)
H_c = Heat of combustion (J/kg) - taken as 2×10^7 J/kg (based on electrolyte)
m = Mass rate of combustion (kg/s) (taken as 1,000 kg of electrolyte over 1800 seconds)

This suggests a relatively high heat flux of 4 MW.

However, in view of the considerable uncertainty associated with making such an estimate of the effective heat flux, and the extent of possible heat losses (e.g. to sprinkler water) the approach adopted was to assume an effective source diameter of 5 m, with a flux of hot air with a vertical velocity of 1 m/s and an excess temperature of 100°C. This corresponds to a lower heat flux of $\pi \times 2.5^2 \times 1 \times 100 \times 1012 \times 0.9 / 10^6 = 1.8$ MW (NB heat capacity of air is 1012 J/°C/kg, density of air at 115°C is 0.9 kg/m^3). The source was conservatively assumed to be located on the lee side of the ISO container at a height of 1 m, leading to significant entrainment in the wake of the container.

Dispersion modelling of the HF releases has been conducted using ADMS 5.2.4 which is well suited to modelling the dispersion of such fire plume releases. In addition to the source term and weather categories referred to above, the following input data has also been used in ADMS.

ISO container dimensions	2.6 m high, 2.4m wide, 12.2 m long
Atmospheric temperature	15°C
Surface roughness length	0.1 m
Surface energy flux	0 kW/m^2 for D2, D5 and D10 conditions; -6 kW/m^2 for F2 conditions
Boundary layer height	800 m for D2, D5 and D10 conditions; 100 m for F2 conditions
Relative humidity	65%
Averaging time	30 minutes

Most of these parameters have relatively little effect on the dispersion results; the most significant inputs being the wind speed and heat flux. The entrainment of the release in the container wake has been included in the ADMS modelling. This entrainment increases as the wind speed increases, and in D10 conditions the release is almost fully entrained in the container wake and the plume centreline is effectively at ground level.

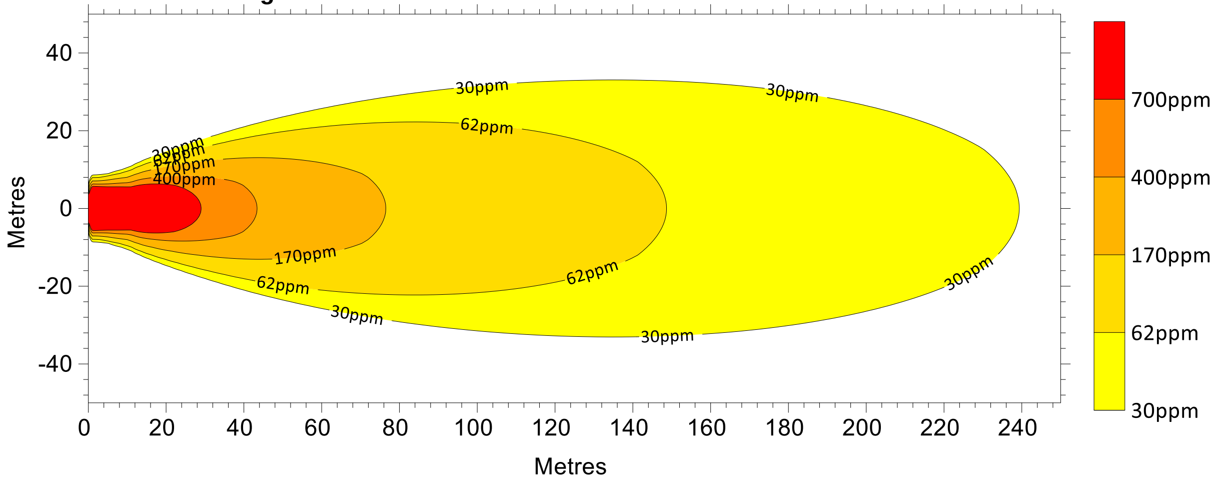
Table 6.1 presents results for the downwind hazard ranges to the HF IDLH, AEGL (10 and 30 minute), HSE SLOT and HSE SLOD for each of the representative weather categories.

Table 6.1 Outdoor Hazard Ranges to SLOT for HF Releases

Criterion	Concentration (ppm)	Outdoor hazard range (m)			
		D2	D5	D10	F2
IDLH	30	85	240	200	85
AELG-3 (30 min)	62	50	150	130	50
AELG-3 (10 min)	170	25	80	70	25
SLOT	400	20	45	40	20
SLOD	700	15	30	30	15

Table 6.1 shows that the worst case hazard ranges tend to occur at moderate wind speeds of 5 m/s. At this wind speed the plume rise is not very significant. As the wind speed increases, the plume rise still decreases, but this is more than compensated by the additional dilution. Figure 6.1 illustrates the ground level concentration results for the worst case D5 weather conditions.

Figure 6.1 HF Concentration Contours in D5 Weather Conditions



It is worth noting that the worst case conditions for toxic hazard ranges may occur in very typical (i.e. D5) weather conditions.

The analysis presented above is considered to be conservative in that the actual heat release rate is likely to be higher, so the worst case conditions would probably occur in higher wind speeds (e.g. D10), but with shorter hazard ranges. There are also some conservatisms in the magnitude of the HF source term, and in the assumption that all the HF is released over 30 minutes, and that people remain exposed in the plume rather than escaping.

It is also noted that, even without a significant fire (due to the fire suppression system), the 2019 McMicken Arizona incident showed that significant concentrations of toxic gases from cell venting, such as HCN and CO, could escape from a container.

7 ASSESSMENT OF WASHOUT AND DEPOSITION

Any fire plume which contains particulates will tend to deposit these particles to the ground, which can lead to issues relating to foodstuffs and clean-up.

Whilst a fire involving a BESS ISO container may generate some such particulate matter, including metal oxides, this has not been regarded as a significant issue in the literature.

Similarly, if there is rain, or water sprays are used on the fire, then there will be some washout (wet deposition) of both particulate and soluble gases. It is noted that gases such as HF are reasonably soluble in water, so water curtains are sometimes used to reduce the airborne concentration of HF following an HF release.

This washout can lead to contamination of ground and water, but again it is not considered to be a significant issue in the literature.

8 FIREWATER RUN-OFF

The HSEGB generally assesses major fires using methods developed by Carter (1989 and 1991) and Atkinson and Briggs (2019). Atkinson and Briggs (2019) state that:

> *There are many examples of chemical warehouses fires that have caused major environmental damage through contaminated firewater run-off. One use of fire plume toxicity assessment is to support “let burn” decisions in planning for and dealing with large fires.*

It is noted that a major concern at the Carnegie Road fire (see Table 2-1) was fire water run-off and potential environmental harm.

There is currently no good data on the significance of firewater from such fires in terms of their impact on the environment, but it is likely to be similar to that from comparable sized fires involving plastics and packaging. There may be specific concerns if the firewater is not contained and can reach sensitive environmental receptors.

9 SUMMARY

This Technical Note provides a high level review of the major hazard issues associated with large scale Battery Energy Storage System (BESS) sites using lithium-ion batteries in an ISO container. It is emphasised that the intention was not to provide a comprehensive review or assessment, but to provide an overall understanding of the key issues, with the principle aim of assisting HSENI to provide more informed advice.

The review has considered published literature and project documents provided by HSENI to establish current best practice for the analysis of such hazards, in terms of source terms and heat loads. A number of incidents involving lithium-ion batteries have been reviewed to provide context and understanding, and some quantitative assessment of fire and explosion hazards has been presented, concentrating on the hazards associated with explosions and dispersion of the toxic fire plume.

Key points which have been identified in the course of producing this Technical Note are:

- Any ISO container BESS has the potential to catch fire due to an unpredictable and spontaneous thermal runaway in a cell. The event may escalate to a fire involving the entire container. There is also a potential for an explosion. The design and mitigation measures in place should ensure that thermal runaway events do not escalate to involve an entire ISO container, but this remains a credible event which should be considered for emergency planning purposes.

- The generation of toxic combustion products from such fires can pose a hazard to those in the vicinity. The main concern appears to be hydrogen fluoride, although there are many other toxic combustion products. Toxic gases such as CO and HCN can also be generated in vent off-gas. This Technical Note provides a reasonably cautious assessment of the HF dispersion and hazard ranges for a worst case fire event, and shows that the HSE SLOT could be exceeded at up to about 45 m, with much higher concentrations in the immediate vicinity.

- The most significant risk to those in the immediate vicinity, or to firefighters, is from potential explosions of flammable vent gases from cells failing due to thermal runaway (either with or without fire). This Technical Note provides some predictions of the potential consequences of such explosion events in terms of the possible levels of blast overpressure. It is noted that there have been several incidents involving significant explosions at BESS sites. It is recognised that cells and modules can undergo cascading thermal runaway without any flaming or ignition, and still generate significant quantities of toxic and flammable gas, with the potential for a delayed explosion.

It is stressed that the assessment of BESS containers in terms of major accident hazard analysis is a new and rapidly developing area, and whilst the assessments here are considered to be reasonably robust, and consistent with current thinking, it is likely that there will be significant developments in the coming months and years.

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Safety of Grid Scale Lithium-ion Battery Energy Storage Systems

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Safety of Grid Scale Lithium-ion Battery Energy Storage Systems

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Sources of wind and solar electrical power need large energy storage, most often provided by Lithium-Ion batteries of unprecedented capacity.

Incidents of serious fire and explosion suggest that the danger of these to the public, and emergency services, should be properly examined.

5 June 2021

Executive Summary

1. Li-ion batteries are dominant in large, grid-scale, Battery Energy Storage Systems (BESS) of several MWh and upwards in capacity. Several proposals for large-scale solar photovoltaic (PV) "energy farms" are current, incorporating very large capacity BESS. These "mega-scale" BESS have capacities many times the Hornsdale Power Reserve in S. Australia (193 MWh), which was the largest BESS in the world at its installation in 2017.
2. Despite storing electrochemical energy of many hundreds of tons of TNT equivalent, and several times the energy released in the August 2020 Beirut explosion, these BESS are regarded as "articles" by the Health and Safety Executive (HSE), in defiance of the Control of Major Accident Hazards Regulations (COMAH) 2015, intended to safeguard public health, property and the environment. The HSE currently makes no representations on BESS to Planning Examinations.
3. Li-ion batteries can fail by "thermal runaway" where overheating in a single faulty cell can propagate to neighbours with energy releases popularly known as "battery fires". These are not strictly "fires" at all, requiring no oxygen to propagate. They are uncontrollable except by extravagant water cooling. They evolve toxic gases such as Hydrogen Fluoride (HF) and highly inflammable gases including Hydrogen (H_2), Methane (CH_4), Ethylene (C_2H_4) and Carbon Monoxide (CO). These in turn may cause further explosions or fires upon ignition. The chemical energy then released can be up to 20 times the stored electrochemical energy. Acute Toxic gases and Inflammable Gases are "dangerous substances" controlled by COMAH 2015. Quantities present "*if control of the process is lost*" determine the applicability of COMAH.
4. We believe that the approach of the HSE is scientifically mistaken and legally incorrect.
5. "Battery fires" in grid scale BESS have occurred in South Korea, Belgium (2017), Arizona (2019) and in urban Liverpool (Sept 2020). The reports into the Arizona explosion [8, 9] are revelatory, and essential reading for accident planning. A report into the Liverpool "fire" though promised for New Year 2021, has not yet been released by Merseyside Fire and Rescue Service or the operator Ørsted; it is vital for public safety that it be published very soon.
6. No existing engineering standards address thermal runaway adequately, or require measures (such as those already used in EV batteries) to pre-empt propagation of runaway events.
7. Lacking oversight by the HSE, the entire responsibility for major accident planning currently lies with local Fire and Rescue Services. Current plans may be inadequate in respect of water supplies, or for protection of the local public against toxic plumes.
8. The scale of Li-ion BESS energy storage envisioned at "mega scale" energy farms is unprecedented and requires urgent review. The explosion potential and the lack of engineering standards to prevent thermal runaway may put control of "battery fires" beyond the knowledge, experience and capabilities of local Fire and Rescue Services. BESS present special hazards to fire-fighters; four sustained life-limiting injuries in the Arizona incident.
9. We identify the well-established hazards of large-scale Li-ion BESS and review authoritative accounts and analyses of BESS incidents. An internet video [10] is essential initial instruction.
10. We review engineering standards relating to Li-ion BESS and concur with other authorities that these are inadequate to prevent the known hazard of "thermal runaway". We conclude that large-scale BESS should be COMAH establishments and regulated appropriately. We respectfully request evidence from the HSE that "mega-scale" BESS are *not* within the scope of COMAH.
11. We seek the considered response of relevant Government Departments as well as senior fire safety professionals to these concerns.

Contents

1. Introduction

Lithium-ion (Li-ion) batteries are currently the battery of choice in the 'electrification' of our transport, energy storage, mobile telephones, mobility scooters etc. Working as designed, their operation is uneventful, but there are growing concerns about the use of Lithium-ion batteries in large scale applications, especially as Battery Energy Storage Systems (BESS) linked to renewable energy projects and grid energy storage. These concerns arise from the simple consideration that large quantities of energy are being stored, which if released uncontrollably in fault situations could cause major damage to health, life, property and the environment.

Table 1. Comparison of some recent "battery fires" since 2014.
Note: this is not a comprehensive list of all Li-ion BESS battery "fires."

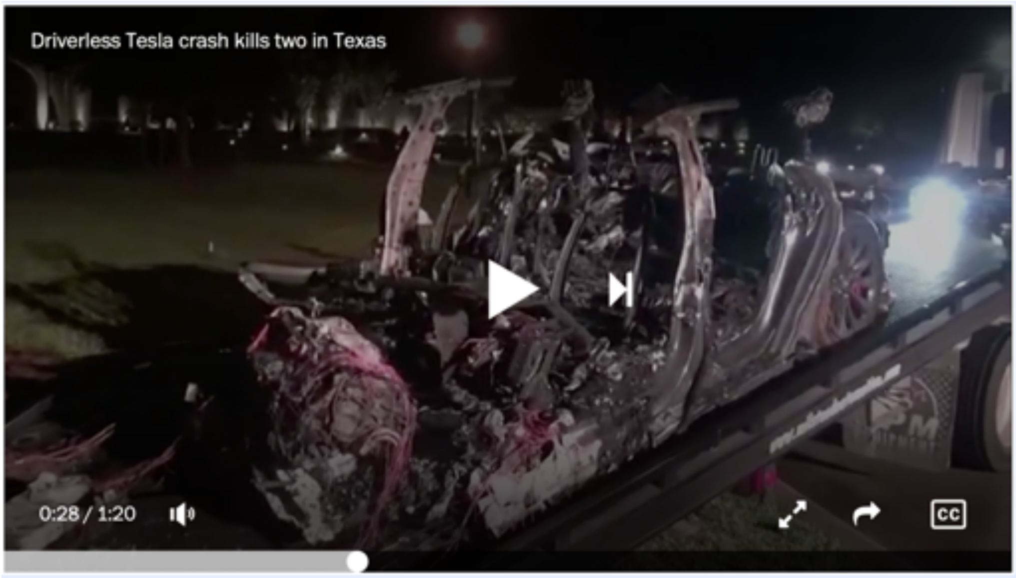
Location	Size	"Battery fire" cause	Time to bring under control	Water needed for cooling	Comments
Houston, Texas, April 2021	0.1 MWh	Driverless vehicle crash	4 hours	30,000 (US) gallons	Tesla Model S
South Korea	Various; 21 fires during 2018-19	Not known to Korean Ministry of Trade Industry and Energy	various	Not known	522 out of 1490 ESS facilities in Korea suspended (Korea Times 2 May 2019)
Drogenbos, Belgium. 2017	1 MWh	Not known.	"rapidly extinguished"	Not known	Occurred during commissioning of system by ENGIE
McMicken Facility Arizona, USA. 2019	2 MWh	Thermal runaway in a single rack out of 27 that were in the cabin – hence 74 kWh electrochemical energy released – less than the Tesla Model S crash.	2 hours from first report to "deflagration"		Explosion as H_2 and CO mixed with air and ignited. Critically injured 4 fire-fighters. Extensive forensic report.
Carnegie Rd, Liverpool, UK, 2020	20 MWh	Not known	11 hours		Full report [1] delayed 4 months; still unpublished.

Even battery electric vehicle (BEV) batteries store energy sufficient for "fires" that have taken hours to control. A Tesla Model S crashed In Texas on the weekend of 17-18 April 2021 igniting a BEV battery fire that took 4 hours to control with water quantities variously reported [2] as 23,000 (US) gallons or 30,000 gallons (87 -115 m^3). Yet the energy storage capacity in even the latest Tesla Model S vehicles is only 100 kWh. This is 1/20 the size of the BESS in Arizona [3] which failed in 2019, and 1/200 the size of the BESS in Liverpool [4] which caught fire [5] in September 2020, and 1/7000 the capacity of the Cleve Hill Solar Farm and Battery Store [6] approved in May 2020.

The past decade has seen a number of serious incidents in grid-scale BESS, which are summarised in Table 1. Despite these incidents, and our growing understanding of these, these large scale Li-ion BESS are not currently regarded by HSE as regulated under the COMAH

Regulations 2015. The legal basis for this attitude is unclear – simple calculations summarised in this paper argue that they should be – and the issue may yet be challenged in judicial review.

The reason the COMAH regulations should apply is the scale of evolution of toxic or inflammable gases that will arise in BESS "fires". In the Drogenbos incident (2017, Table 1), the inhabitants of Drogenbos and surrounding towns were asked to keep all windows and doors shut; 50 emergency calls were made from people with irritation of the throat and airways[1]. A chemical cloud which "initially had been enormous", was charted by helicopter. The Belgian Fire Services could not control what was described as "the chemical reaction" and filled the cabin with water. Fears of an explosion with 20 metre flames kept people confined for an hour. Although the initial visible flames were controlled quickly, cooling continued over the next 36 hours.



Two men died after a Tesla vehicle, which authorities said was operating without a driver, crashed into a tree in a Houston suburb on April 17. (Reuters)

Figure 1: Remains of the Tesla Model S crash and fire, 17 Apr 2021, after 4 hours and 30,000 gallons. Battery capacity 100 kWh.

Figure 2: Remains of a Korean BESS destroyed by a "battery fire". An energy storage system was destroyed at the Asia Cement plant in Jecheon, North Chungcheong Province, on Dec. 17. Courtesy of North Chungcheong Province Fire Service Headquarters (Korea Times 2 May 2019)

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[1] Tom Vierendeels (2017) "Explosiegevaar by brand in Drogenbos geweken : 50-tal oproepen van mensen die zich onwel voelen door rook." *Het Laatste Nieuws,* 11 November 2017

Figure 3: “Battery Fire” at Drogenbos, Belgium 11 Nov 2017. Taken at the start of the incident and 15 minutes later (eye-witness footage). 1 MWh facility; fire occurred during commissioning.

Figure 4: The 2 MWh McMicken (Arizona) BESS after the explosion on 19 April 2019

Figure 5: The 20 MWh BESS at Carnegie Rd, Liverpool. Courtesy Ørsted.

Figure 6: The fire at Carnegie Road, 15 Sep 2020. Liverpool Echo report, which took 11 hours to control.

The incidents recorded in Table 1 are all in relatively small BESS or a single BEV. Yet “mega-scale” BESS are now planned on a very large scale in many current proposals in the UK, listed in Table 2 and illustrated in the subsequent Figures.

And no engineering standards are currently applied to pre-empt future accidents in grid-scale BESS, the most critical of which would be design features aimed at preventing the phenomenon of “thermal runaway”, the process whereby failure in single cell causes over-heating and then propagates to neighbouring cells so long as a temperature (which can be as low as 150 °C) is maintained.

BEV batteries do now include thermal barriers or liquid cooling channels between all cells to safeguard against this phenomenon, but no such engineering standards exist for grid-scale BESS. A large BESS can pass all existing engineering design and fire safety test codes and still fail in thermal runaway – by now a well-known failure mode. This must be urgently addressed.

The consequences of major BESS accidents could be significant and emergency services need adequate plans in place to handle any such incident.

Table 2. “Mega” scale solar plant and/or Li-ion BESS in Australia and the UK*

Project	Location	Status	Solar PV Scheme Size	Battery Stores	Battery type	Battery capacity
Hornsdale Power Reserve	S. Australia	Operational	Not directly associated	Single site	Li-ion	193 MWh
Cleve Hill Solar + Battery Store	Kent	Permission granted (2020)	350 MW; land coverage 890 acres	Single site	Li-ion	700 MWh
Sunnica Solar + Battery Store(2)	Cambridgeshire/ Suffolk	Pending submission	500 MW; land coverage approx. 2792 acres	31.5 ha of land over 3 compounds [7] of 5.2, 10.7 and 15.6 ha	Li-ion	Undeclared. Estimate 1500 – 3000 MWh
Longfield Solar + Battery Store	Essex	Pending statutory consultation	500 MW; land coverage approx. 1400 acres	Stated as 3.7 acres: number of sites TBD	Li-ion	Undeclared. Estimate: 150 MWh

* Li-ion technology has been assumed in all these proposals as Li-ion battery electrochemistry is dominant in grid-scale BESS applications (deployment at this scale is unlikely to involve technologies with lesser experience). Estimated values for Battery Capacity for the Sunnica are calculated based on the McMicken facility in Arizona (Appendix 1) and the Cleve Hill DCO. For the Longfield site it is estimated from Energy Institute guidance on energy density [25] at about 100 MWh ha^{-1}. The exact specification for the battery units has not been disclosed by the developers at this present time.

Figure 7: The Hornsdale Power Reserve (South Australia) in the process of expansion from 100 MW/129 MWh to 150 MW/193.5 MWh, as of November 2017.

Plate 3-10. Typical battery storage compound configuration (*image reproduced courtesy of Fluence Energy*).

Figure 8: a “typical” BESS compound (abstracted from Sunnica PEIR, Ch 3)

Figure 9: Artists impression of Tesla 250 MWh “Megapack”.
Sunnica may have 3 ×this capacity in just one of its three BESS compounds.

2. Leading Concerns

The main concerns regarding large scale Li-ion BESS are:

1) The potential for failure in a single cell (out of many thousands) to propagate to neighbouring cells by the process known as “thermal runaway”. Believed to be initiated by lithium metal dendrites growing internally to the cell, a cell may simply discharge internally releasing its stored energy as heat. Even sound Li-ion cells will spontaneously discharge internally if heated to temperatures which can be as low as 150 °C, releasing their stored electrical energy, thus overheating neighbouring cells and so on. Temperatures sufficient to melt aluminium (660 °C) at least have been inferred from analyses of such thermal runaway accidents. Eye-witness reports consistently speak of repeated “re-ignition” which is inevitable, even in the complete absence of oxygen, so long as the temperature anywhere exceeds the thermal runaway initiation threshold.
2) The emission of highly toxic gases – principally Hydrogen Fluoride – for prolonged periods, in the event of thermal runaway or other battery fires. At a minimum, respirators and complete skin protection would be required by any fire-fighters. Measures to protect the public from toxic plumes would also be necessary.
3) The emission of large quantities of highly inflammable gases such as Hydrogen, Methane, Ethylene and Carbon Monoxide even if a fire suppression system is deployed. These gases will be evolved from a thermal runaway accident regardless of such measures, with explosion potential as soon as they are mixed with air and in contact with hot surfaces. Such an explosion was the cause of the “deflagration event” at McMicken, Arizona in 2019 in a 2 MWh BESS, which critically injured four fire-fighters and was triggered simply by opening the cabin door.
4) The absence of any adequate engineering and regulatory standards to prevent or mitigate the consequences of “thermal runaway” accidents in Li-ion BESS.
5) The potential for thermal runaway in one cabin propagating to a neighbouring cabin. In Arizona [3] there were reports of *“fires with 10-15 feet flame lengths that grew into 50 - 75 feet flame lengths appearing to be fed by flammable liquids coming from the cabinets*”.
6) The significant volumes of water required to thoroughly cool the system in the event of a “fire”, and how this water will be contained and disposed of (since this will be contaminated with highly corrosive hydrofluoric acid and, therefore, must not be allowed to drain into the surrounding environment).

Such incidents are routinely and repeatedly described in the Press as “battery fires” though they are not “fires” at all in the usual sense of the word; oxygen is completely uninvolved. They represent an electrochemical discharge between chemical components that are self-reactive. They do not require air or oxygen at all to proceed.

Hence the traditional “fire triangle” of “Heat, Oxygen, Fuel” simply does not apply, and conventional fire-fighting strategies are likely to fail (Figure 10, over).

Thermal runaway events are uncontrollable except by *cooling* all parts of the structure affected – even the deepest internal parts – below 150 °C. This basically requires water, in large volumes.

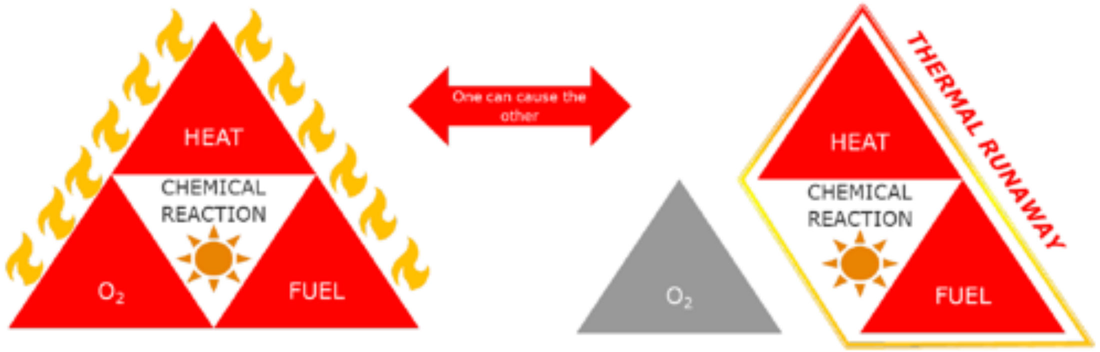

Figure 11 The fire triangle and its relationship to thermal runaway

Figure 10: The traditional "fire triangle" does not apply to "thermal runaway".

3. Thermal Runaway (Battery "fires")

Li-ion batteries are sensitive to mechanical damage and electrical surges, both in over-charging and discharging. Most of this can however be safeguarded by an appropriate Battery Management System (BMS) and mechanical damage (unless deliberate and malicious) should not be a hazard. Internal cell failures can arise from manufacturing defects or natural changes in electrodes over time; these must be regarded as unavoidable in principle. Subsequent escalation into major incidents can propagate from such apparently trivial initiation.

In July 2020 a thorough failure analysis by Dr Davion Hill of DNV GL [8] was prepared for the Arizona Public Service (APS), following the April 2019 thermal runaway and explosion incident in the 2 MWh Li-ion BESS facility at McMicken, Arizona. This report is revelatory and more detailed than any other failure analysis known to us. It is essential reading for any professional involved in fire safety planning for major BESS. (Figures 11 to 13).

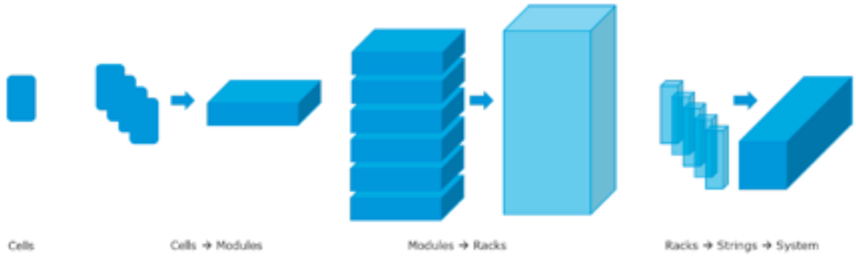

Figure 11: Cells stack into Modules; Modules into Racks; Racks into Strings; Strings into Systems.

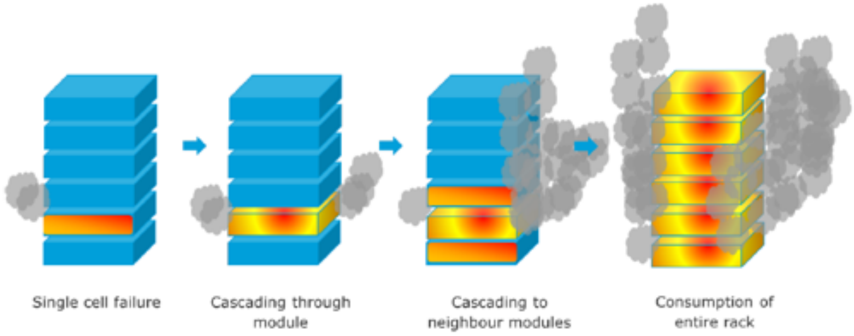

Figure 25 A single cell failure propagated through Module 2, then consumed the whole rack, releasing a large plume of explosive gases. This process could have occurred without visible flame, which would explain why the gases were not burned as they were emitted.

Figure12: Propagation of single Cell failure through Module; cascade to entire Rack.

A report by Underwriters Laboratories (UL) on the same incident [9] is less technical on the physics and engineering of the underlying causes and failure modes, but more comprehensive in terms of practical situations and consequences found, and suffered, by the “first-responders”. Two fire-fighters suffered life-limiting brain injuries, one suffered spinal damage and fourth facial lacerations. This report is similarly essential reading for any fire and emergency response planning.

Figure 13: Destruction of Rack at McMicken.

Detail: molten aluminium pools (exceeded 660 °C)

Figure A.1: Photograph taken during decommissioning of the ESS shows a pool of solidified aluminum on the floor in front of Rack 15 [11].

Forensic analysis [8] of the 2019 Arizona “fire” identified a failure mode different from mechanical abuse or electrical mis-management. The initiating failure was localised to a single cell at a known position in the rack. Although the cell itself was of course destroyed during the incident, the failure mode is believed to have been lithium metal deposition and abnormal growth of lithium metal dendrites. These phenomena were also found in randomly selected *undamaged* cells from the same BESS and also from a different BESS of the same manufacture elsewhere. These phenomena must be regarded as common, and inherent to the cells themselves.

The lithium metal deposits will react with air moisture, causing overheating and smoke. Battery swelling, electrolyte degradation, and internal short circuits are all possible modes of failure with internal discharge and generation of locally intense heat.

Because of the known thermal breakdown of even non-faulty cells, above a threshold temperature (which can be as low as 150 °C), the loss of even a single individual cell can rapidly cascade to surrounding cells, resulting in a larger scale “fire.” This is “thermal runaway” in which failures propagate from cell to cell within “modules” and from module to module within a “rack”.

This is what happened at McMicken [8], with temperatures sufficient to melt Aluminium (660 °C) being reached. Such “fires” can be extremely dangerous to fire fighters and other first responders because, in addition to the immediate fire and explosion risks, they would have to deal with toxic gases (principally hydrogen fluoride HF, also hydrogen cyanide HCN and other fluorine compounds such as phosphoryl fluoride POF_3) and exposure to other hazardous materials.

Rack to rack propagation fortunately did not happen at McMicken, though an explosion did [8]. A local conventional fire involving the plastics materials or gases evolved from them could have initiated rack-to-rack propagation; the only essential factor would have been sufficient heat to trigger thermal breakdown in just one cell in a neighbouring rack. Li-ion cells have been observed to eject molten metal during thermal runaway, another possible mode of propagation over distance. Propagation through a subsequent rack would then occur by exactly the same thermal runaway mechanisms, and potentially beyond between neighbouring cabins in large-scale BESS.

Thermal runaway is illustrated in dramatic fashion with tiny commercial Li-ion cells in a useful internet video [10] (Figure 14). The commercial cells involved in this demonstration have tiny capacities: a mere 2.6 Ah or about 10 Wh for typical terminal voltages.

A Tesla Model S would have the capacity of about ***10,000*** such cells.
A 20 MWh BESS has the capacity of about ***2 million*** such cells.

In the video, the cell is deliberately over-heated on a small electric stove. The fully charged cell goes into thermal breakdown, eventually rupturing the can. The cell flies off as a rocket and seconds later is discharged but red hot and will burn anything combustible. Although not illustrated, it is evidently hot enough to produce the same thermal breakdown in an adjacent cell within a battery.

This illustrates the damage done to a non-faulty cell, simply by overheating externally.

Figure 14: (a) A charged 2.6 Ah cell being deliberately overheated. (b) at the point of rupture (c) the cell takes off as a rocket (d) seconds later the discharge is complete, and the cell is red hot.

4. Toxic and flammable gas emissions

During a Li-ion “battery fire,” multiple toxic gases including Hydrogen Fluoride (HF) [11], Hydrogen Cyanide (HCN) [13] and Phosphoryl Fluoride (POF_3) [11] may be evolved. The most important is Hydrogen Fluoride (HF), which may be evolved in quantities [11] up to 200 mg per Wh of energy storage capacity.

HF is toxic in ppm quantities and forms a notoriously corrosive acid (Hydrofluoric Acid) in contact with water. It is toxic or lethal by inhalation, ingestion and by skin contact. The ERPG-2 concentration (1 hour exposure causing irreversible health effects) given by Public Health England is just 20 ppm; the workplace STEL (15 minute Short-Term Exposure Limit) is just 3 ppm [12]. Major emissions of HF would form highly toxic plumes that could easily threaten nearby population centres, workplaces and schools.

Appendix 3 contains calculations of projected toxic gas quantities for 3 grid-scale battery stores that have been approved or are pending review by the Planning Inspectorate (Table 2).

The calculated capacities at the “mega-scale” sites listed in Table 2 are tens, or even hundreds, of times larger than the facilities in Table 1, which experienced significant fires or explosions.

In addition to evolution of toxic gases, even in an inert atmosphere (without Oxygen), multiple flammable gases (such as Hydrogen H_2, Carbon Monoxide CO, Methane CH_4, and Ethylene C_2H_4) would be evolved during thermal runaway. These are “typical of plastics fires” [8] and have been measured in sealed vessel tests [13]. As noted by Hill/DNV [8] and others [13], the proportions of H_2, CO, CH_4 and C_2H_4 do not in fact vary greatly between different cell technologies, simply because the chemical nature of the envelope polymers, separators, electrolyte solvents and electrolytes themselves do not differ greatly. The variations between Li-ion technologies are in the electrode systems, which are typically not polymeric.

Such inflammables can clearly create (ordinary, air-fuel) fires or explosions once mixed with air/oxygen. It is important to note that the Heats of Combustion of the inflammables may be up to 15 – 20 × the rated electrical energy storage capacity of the BESS. This has been demonstrated by the same tests which determined the quantities of HF evolved [11]. These were fire tests, not sealed vessel tests [13]. The stored electrical energy is therefore by no means a conservative estimate of the total energy release which could be released in a major (air-fuel) fire in a BESS, irrespective of whether the initiating cause was a conventional fire or Li-ion cell thermal runaway.

Appendix 2 estimates the inflammables potentially evolved from the BESS given in Table 2.

5. Total Energy Release Potential

Any large energy storage system has the risk that energy released in malfunction will be uncontrollable in ways that will do major damage. BESS can release electrochemical energy in the form of thermal runaway or "battery fires". In addition they can release chemical energy in the form of explosions or conventional fires of inflammable gases, or of polymer components. Many thermal runaway "fires" have now happened, as has explosion of evolved inflammable gases.

An important indicator of the foreseeable scale of a "worst credible hazard" is provided by the total stored energy in the system. For BESS, this comprises two components:

(i) The stored electrical energy which might be released in the event of thermal runaway incidents, a self-reactive electrochemical energy release not requiring oxygen at all, and

(ii) Stored chemical (fuel) energy which might be released in complete combustion of the inflammable gases which might be released by (i).

Electrochemical energy release is uncontrollable once started, by any measure except cooling – of all cells and cell parts – below about 150°C. Water is the only fire-fighting substance with the necessary heat capacity. Concurrent conventional fire would first heat cells above the thermal runaway temperature, causing more thermal runaway. Chemical energy release from inflammable gases is also uncontrollable once those gases are mixed with air and ignited: explosions result.

What might be the scale of such energy releases? The Sunnica proposal is estimated to have a stored energy between 1.5 – 3.0 GWh in total, spread across 3 separate sites called Sunnica East A, Sunnica East B and Sunnica West A (see calculations in Appendix 1). It is between 2 – 4 times the capacity projected for Cleve Hill (700 MWh). It is 8 – 15 times the capacity (193 MWh) of the "Hornsdale Power Reserve" in Australia, at installation (2017) the world's largest.

Compared to other energy storage technologies, the Dinorwig Pumped Storage Scheme in Snowdonia stores about 9 GWh [14]; the Sunnica BESS corresponds to 17 – 33 % of Dinorwig.

Compared to major explosions, the energy released in the Beirut warehouse explosion of August 2020 has been estimated [15] by Sheffield University at about 0.5 kilotons of TNT (best estimate) with a credible upper limit of 1.12 kilotons. A totally independent estimate [16] (based on seismic propagation instead of eye-witness footage) gives the same range, without specifying a "best" estimate. The popular measure of major explosions in "kilotons of TNT" has an agreed definition[2] of 1.162 GWh of released energy; in this paper we shall take "one Beirut" to be an explosive energy of 0.5 kilotons of TNT or about 580 MWh of released energy.

The projected BESS storage at Sunnica corresponds to 1.4 – 2.7 kilotons of TNT in total, across all three sites. In the "low" case, this would be "0.92 Beiruts" at the Sunnica West A site alone, or "2.7 Beiruts" over the whole scheme. In the "high" case "2.7 Beiruts" could be stored in the Sunnica East B site alone. Note that these are stored electrochemical energy only; the potential for conventional fire or explosion of evolved inflammables could be **up to 20 × larger** [11]. See Table 3, Appendix 1.

This is plainly a quantity of stored energy which, if released uncontrollably, could do major damage. Explosions and fires at individual BESS are matters of record. They can propagate from failure in a single cell out of many thousands. Cell-to-cell and module-to-module propagation occurred at McMicken. Rack-to-rack propagation was avoided, but could readily occur if continuous

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[2] See e.g. Wikipedia.

fires start. Cabin-to-cabin propagation of a major BESS “battery fire” would be the critical link that would escalate major but manageable fires into catastrophes.

Yet this propagation route remains unanalysed. Significantly, Commissioner Sandra D Kennedy of the Arizona State Commission [3] reviewed reports on the 2019 McMicken battery fire and also a 2012 battery fire at the APS Eldon substation facility in Flagstaff, AZ. She quotes the Flagstaff fire department report on the latter incident as referencing :

> “*Fires with 10-15 feet flame lengths that grew into 50 - 75 feet flame lengths appearing to be fed by flammable liquids coming from the cabinets*”.

Finally, in the context of BESS, “Stranded Energy” will remain a hazard at any affected BESS cabins even assuming an initial incident is controlled. The accident investigation at McMicken required nearly 3 months, simply to discharge “stranded energy” safely [8].

‘”Mega-scale” Li-ion BESS should, in all prudence, require the highest level of regulation. The COMAH regulations are designed for this, including establishments where dangerous substances may be generated “if control of the process is lost” [17] in a thermal runaway accident.

6. Applicability of the COMAH (Control of Major Accident Hazard) Regulations 2015

The governing criteria for application of the COMAH Regulations [17] are:

1. The presence of hazardous materials, or their generation, "if control of the process is lost."
2. The quantity of such hazardous materials present or that could be potentially generated.

There is no doubt that hazardous substances such Hydrogen Fluoride (an Acute Toxic controlled by COMAH) would be generated in a BESS accident (i.e., in "battery fires"). Similarly highly Inflammable Gases (also controlled by COMAH) would be evolved even if the atmosphere remained oxygen-free. Depending on the size of the "establishment" these could be produced in sufficient quantities to be in the scope of COMAH. In Appendix 2 we estimate quantities guided by the literature, where fire tests have directly measured evolution of the hazardous gases.

For small capacity BESS installations, under 25 MWh capacity, the quantities ("inventory") of the evolved hazardous substances might be outside COMAH. This paper however addresses the recent trend towards "mega-scale" Li-ion BESS (Table 2) with very large quantities of stored energy, where the inventory should be large enough to bring the installation within scope.

Broadly speaking, the threshold for applicability of COMAH will be dependent on the precise BESS technology chosen, but likely to be for BESS in the region of 20 – 50 MWh. See Appendix 2.

A letter to the HSE regarding applicability of COMAH to large-scale BESS (dated 25 Nov 2020 [18]) received no reply until follow-up letters were sent addressed personally to the Chief Executive on 7 February 2021, with the intervention of Mrs Lucy Frazer MP. The reply from the Chief Executive [19] dated 22 February 2021 stated that "*Li-ion batteries are considered articles and are not in scope of COMAH*".

We believe the current attitude of the HSE – that even large-scale Li-ion BESS are "articles" best regulated by operators – is not consistent with the law.

Unless tested in the Courts however, this throws the entire responsibility for ensuring the safety of major BESS "battery fires" onto the Fire and Rescue Services. Currently the HSE makes no representation to the Planning Inspectorate in respect of BESS hazards.

7. Engineering standards for BESS

As with any hazard, the basic principles of Prevention and Mitigation must be applied to minimise the risk to life, property and the environment. A major contribution of the Hill/DNV report [8] is a review of current engineering and fire protection standards. This did not concern planning, siting and electrical standards, but simply addresses the question: which standards, if any, offer Prevention or Mitigation of the phenomenon of thermal runaway? The answer appears to be none.

"Thermal runaway" is an electrochemical reaction, well-known in Li-ion BESS, that is largely uncontrollable once started. Since failures in single cells (among many thousands) can be sufficient to initiate thermal runaway, the only known Prevention measure is that adopted by the BEV industry, viz. thermal isolation of neighbouring cells, so that if failure occurs in any one cell, insulation or water cooling prevents easy thermal spread to neighbouring cells. Various design strategies have been adopted in BEV Li-ion batteries, usually involving some form of thermal barrier.

However these are not widely used in grid-scale Li-ion BESS. Current practice is the assembly of stacks of cells, typically "pouch" cells which are externally flat polymer bags, that are stacked side by side in low profile modules with no thermal isolation. This is not the construction adopted in current generation BEV batteries; BEV practice *(with* thermal isolation) extended to grid-scale BESS would obviously increase costs and complexity considerably.

The engineering standards reviewed by Hill/DNV [8] included NFPA 855, UL 1973 and UL 9540/9540A. UL 9540A is a US standard that is widely used in grid-scale BESS engineering, is routinely recommended by insurance and risk consultants [20] and was appealed to by the developer of the Cleve Hill solar farm (Table 2). The problem is that UL9540A is fundamentally a test procedure. It mandates no design features. It requires absolutely nothing that would prevent thermal runaway in any BESS design. This means that an operator can say truthfully that a given BESS is "fully compliant" with UL9540A, yet this would provide no assurances at all regarding thermal runaway prevention. It is therefore wholly insufficient as a safeguard to either the operator, the public, or to emergency services.

NFPA 855 [21], uniquely, requires evaluation of thermal runaway in a single module, array or unit and recognises the need for thermal runaway protection. However, it assigns that role, with complete futility, to the Battery Management System (BMS). Thermal runaway is an electrochemical reaction which once started cannot be stopped electrically. It is uncontrollable by electronics or switchgear. A BMS can locate faults, report and trigger alarms, but it cannot stop thermal runaway.

The Hill/DNV report [8] highlights the many shortcomings of existing standards, see Appendix 4. The basic issue is simple:

(1) Thermal Runaway has very few means of Mitigation once started.
(2) It is therefore essential to address Prevention as a priority.
(3) ***No current engineering or industry standards require the Prevention of thermal runaway events by thermal isolation barriers.***

Nothing in existing standards prevents runaway incidents happening again, requiring for initiation only single-cell failures from known common defects in cell manufacture.

8. Fire Safety Planning for BESS "fires"

Taking the recent Sunnica BESS proposal as an example, a joint statutory consultation response has been submitted by the four Local Authorities concerned. The Local Authorities in this case are Cambridgeshire and Suffolk County Councils, and West Suffolk and East Cambridgeshire District Councils. This joint consultation response [22] included a section on Battery Safety (pp 74-75) and states as follows:

Suffolk Fire and Rescue Service (SFRS) *will work and engage with the developer as this project develops to ensure it complies with the statutory responsibilities that we enforce.*

Sunnica should produce a risk reduction strategy as the responsible person for the scheme as stated in the Regulatory Reform (Fire Safety) Order 2005. It is expected that safety measures and risk mitigation is developed in collaboration with services across both counties.

The response also later states: *As with all new and emerging practices within UK industry, the* ***SFRS would like to work with the developers*** *to better understand any risks that may be posed and develop strategies and procedures to mitigate these risks.*

It is clear that local Fire and Rescue Services have been given the lead responsibility for independent emergency planning, in concert with the developers. Because of the attitude of the HSE refusing to exercise regulatory control over BESS safety, local Fire and Rescue Services become the sole independent public body able to influence BESS safety issues at the planning stage.

Many detailed recommendations have been made by the Local Authorities in the case of Sunnica. It is unclear how much opportunity or input Suffolk FRS has had in these. However the recommendations offered betray some serious misunderstandings and a complete lack of awareness of the lessons and recommendations made in publicly available documents such as the Hill/DNV report [8] into the McMicken explosion.

These are taken point by point in Appendix 4 but some general points are made here.

1. Thermal runaway cannot be controlled like a regular (air-fuel) fire. The only way to mitigate "re-ignition" (a regular report of eye-witnesses) is by thorough cooling. Water is the only fire-fighting material with the necessary thermal capacity. Sprinkler systems, though with good records in conventional building fires, are likely to be completely inadequate. The purpose of the water is absorbing a colossal release of energy. The Hill/DNV report [8] called for so-called "dry pipe" systems allowing first responders to connect very large water sources to the interior without having to access the interior.

It is critical to appreciate that all parts of the battery system must be cooled down. Playing water on a battery "fire" may cool the surface, but so long as Li-ion cells deep inside the battery remain above about 150°C, "re-ignition" events will continue. It is not sufficient to estimate water requirements on the basis of calculations assuming water reaches everywhere, uniformly.

For example, in the recent Tesla car fire [2] the BEV battery kept re-igniting, took 4 hours to bring under control and used 30,000 (US) gallons of water (115 m^3). This was for a 100 kWh BEV battery, designed with inter-cell thermal isolation barriers.

In the case of Sunnica, the Local Authorities have suggested that water supplies of 1900 litres per minute for 2 hours (228 m^3) will be needed [22]. But this is grossly inadequate. Using the above Tesla BEV fire experience, this amount of water would suffice for just ***two*** Tesla Model S car fires. Scaling this up to even the smallest 2 MWh BESS (such as that in McMicken [8]), which contains stored energy equivalent to ***twenty*** Tesla Model S cars, it is clear to see that a much greater amount of water would be needed.

The actual amount of water required will depend on the energy storage capacity per cabin which, in the case of Sunnica, is still unstated. Some simple estimates are, however, made below. **The requirements suggested to date by the Local Authorities for the Sunnica installation are completely inadequate and, if not addressed, would leave Suffolk FRS without the means to control a major BESS "fire".**

Taking a storage capacity of 10 MWh in just one of the Sunnica cabins (see Appendix 1), a complete thermal runaway accident in such a BESS would release that stored electrochemical energy, plus an indeterminate quantity of heat from combustion of hydrocarbon polymer materials or inflammable gases evolved from them. Such Total Heat Release may be up to twenty times the amount of the stored electrochemical energy in the BESS [11].

The thermal capacity of water is 4.2 kJ kg^{-1} K^{-1} or in kWh terms, about 1.17 kWh m^{-3} K^{-1}. If heated from 25 °C to boiling point about 87.8 kWh m^{-3} of thermal energy is required.

Hence the water volume required to absorb 10 MWh of released energy without boiling is about 114 m^3 or 30,000 US gallons, the same amount as required in practice to control a fire in a single Tesla Model S car with a mere 100 kWh battery, 100 times smaller than a 10 MWh BESS.

The quantity suggested by the Local Authorities' joint response is 228 m^3 (1900 L min^{-1} for 2 hours), twice the above estimate, which would naively be sufficient for a 20 MWh BESS fire. **However, from the experience of recent BEV fires, it could be insufficient by a factor of 100.**

No such calculations were presented in the Examination of the 700MWh Cleve Hill BESS [6].

2. "Clean agent" fire suppression systems are a common fire suppression system in BESS, but are ***totally ineffective*** to stop "thermal runaway" accidents. The McMicken explosion was an object lesson in this: the installed "clean agent" system operated correctly, as designed, on detection of a hot fault in the cabin [8]. There was no malfunction in the fire suppression system. But it was completely useless because the problem was not a conventional fuel-air fire, it was a thermal runaway event. Only water will serve in thermal runaway.

Indeed in the McMicken explosion the "Novec 1230" clean agent arguably contributed to the explosion by creating a stratified atmosphere with an air/Novec 1230 mixture at the bottom and inflammable gases accumulating at the cabin top.

The most probable cause of the explosion was mixing caused by the opening of the door by first responders. The explosive mixture contacted hot surfaces and ignited [8].

3. A further recommendation of the Hill/DNV report [8] into the McMicken explosion is for a means of ***controlled venting*** of inflammable gases ***before*** first responders attempt access. In the Local Authority response to the Sunnica consultation, ventilation is listed as a BESS requirement [22] but the reason given, bizarrely, is "to control the temperature" – at which ventilation or air-conditioning (also listed) would be totally ineffective, lacking any significant thermal capacity.

The critical reason for controlled ventilation is the removal of inflammable gases ***before*** an explosive mixture forms. Deflagration panels (to decrease the pressure of explosions that do occur) are also recommended.

It should be noted that although controlled venting provisions would mitigate the consequence of inflammable gas evolution, they would also require simultaneous venting of Hydrogen Fluroide that would be evolved concomitantly.

Toxic gas hazard would continue to present a risk to the community and the environment for the duration of the incident. Fire-water will be contaminated with, *inter alia*, highly corrosive Hydrofluoric Acid. Contamination of water supplies and waterways ***must*** be prevented.

It is strongly recommended that Fire Services study the Hill/DNV report [8], and the related Underwriters Labs report [9], act upon their recommendations, and make realistic, physics-based, calculations of the water quantities required to be available at every single BESS cabin. There could be as many as 150 BESS cabins at the Sunnica East B site alone – see Appendix 1; each of these would need a sufficient water supply.

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[26] A guide to the COMAH regulations (2015): [redacted]

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Appendix 1: Battery Capacity Calculations for the Grid-scale BESS proposed at the "Sunnica" site.

The Sunnica scheme will be taken as an example of a "mega-scale" solar plant with BESS. If approved, it would cover approximately 2800 acres and will include BESS on 3 separate sites.

The proposed BESS capacity in the Sunnica scheme has not been specified. Estimates of storage capacity can be made on the basis of the land areas allocated to the BESS compounds, assuming full use (per meeting with Parish Councillors, 30 October 2020 [23]). Li-ion battery technology has also been assumed because it is the most widely used in the industry today. Li-ion batteries have a high energy density, and the costs of these have fallen significantly over the past few years [24] .

Land areas and cabin size are quoted in the Sunnica Scheme Description as:

Sunnica East A:	5.23 ha
Sunnica East B:	15.6 ha
Sunnica West A:	10.65 ha
Total:	31.48 hectares.

One storage cabin size is 15 m length × 5 m width × 6 m height. This height is *double* that of a so-called "hi-cube" shipping container and has a larger footprint (75 m^2 *vs* 30 m^2 for a standard 40-foot shipping container).

Storage capacity can be estimated based on other BESS and storage cabin volumes:

Single cabin energy storage capacity:

The McMicken, Arizona, Li-ion BESS was a single cabin, footprint of 60 m^2 and 'shipping container' height. The Sunnica BESS cabins are 75 m^2, with 'double shipping container' height (6 m).
Energy storage at McMicken was 2 MWh.

Scaling by footprint and height yields a *single cabin* energy storage capacity estimate of 5 MWh for each of the "Sunnica" BESS cabins.

The Arizona cabin had empty space for expansion racks, so a larger single cabin energy storage capacity, up to say 10 MWh, is entirely conceivable.

Density of BESS cabins on allocated land:

This is unstated by Sunnica. We assume that 7.5% of the allocated land area will be occupied by the BESS cabins themselves (this allows for safety separations, fire access routes, Battery Management Systems (BMS) and other electrical plant, bunding for firewater in the event of incidents). This implies a total of 315 BESS cabins allocated over the three sites.

Total scheme storage capacity:

5 MWh (single cabin capacity) x 315 cabins yields a total energy storage capacity of **1575 MWh** (or 1.574 GWh), distributed over 3 separate battery compounds of unequal size (31.48 ha total). If the single cabin capacity were 10 MWh, the total doubles to **3150 MWh.**

A storage capacity between 1500 – 3000 MWh is therefore credible for the Sunnica proposal, depending on single cabin storage and the density of cabins on the land.

The area density of storage at this cabin density would be 50 MWh ha^{-1} for a single-cabin storage of 5 MWh. This figure of 50 MWh ha^{-1} is independent of the total area allocated; it depends only on the assumed fraction (7.5%) occupied.

For comparison, the corresponding density at Cleve Hill [3] is a very similar 69.2 MWh ha^{-1}.

The Energy Institute [25] gives 100 MWh ha^{-1} as ‘typical’ for Li-ion BESS planning. This density would be reached in our assumptions if the single cabin capacity were 10 MWh. The latter figure is entirely conceivable because the “base estimate” derives from an incompletely populated cabin. It is also readily achievable if the spacing of cabins is closer than implied by the assumption of 7.5% land occupancy.

The “base case” estimate of 315 cabins and 1574 MWh is an overestimate *only if* the project does *not* fully occupy the allocated land (i.e. BESS cabin density is less than the 7.5% assumed), but this would be contrary to advice from the developer in meetings with local Councillors.

It is also an overestimate if the single cabin storage capacity is less than 5 MWh. This is unlikely because it is estimated from a BESS cabin still incompletely populated.

These estimates are summarised in the following Table.

Table 3. Estimates of electrical stored energy under various assumptions at Sunnica.
Note: “1 kiloton TNT” is equivalent to 1.163 GWh. “One Beirut” is equivalent to 580 MWh.

Compound	**Area**	**No. of cabins at area density of 7.5%**	**Energy storage capacity**		**Comments**
(Single cabin) (per cabin land)	75 m^2 1000 m^2	1	5 MWh	10 MWh	Per cabin assumptions
Sunnica East A	5. 23 ha	52	260 MWh	520 MWh	Per compound estimates of stored energy
Sunnica East B	15.6 ha	156	780 MWh	1560 MWh	
Sunnica West A	10.7 ha	107	535 MWh	1070 MWh	
Whole Scheme	31.5 ha	315	1575 MWh	3150 MWh	Stored electrochemical energy only.
			1.575 GWh	3.150 MWh	
			1.36 kilotons	2.71 kilotons	Does not include chemical energy from inflammables.
			2.72 “Beiruts”	5.44 “Beiruts”	

Appendix 2: Applicability of the COMAH Regulations to large-scale BESS

The COMAH regulations (2015): COMAH regulates establishments with quantities of dangerous substances (categorised as toxic, flammable or environmentally damaging) that are present above defined thresholds. The substances do not need to be present in normal operation. If dangerous substances could be generated "if control of the process is lost", the likely quantity generated thereby must be considered. If the mass of dangerous substances that could be generated in loss of control exceeds the COMAH thresholds, the Regulations apply.

There are two "tiers" to COMAH, the "upper tier" imposing more stringent controls. Thresholds of hazardous substances are listed with thresholds for both tiers.

The regulations specify aggregation rules when more than one substance in a hazard category (e.g. flammables) may be present; even if all such substance are below the COMAH thresholds, others in the same hazard category must be quantified and the proportions of the threshold aggregated. If the total exceeds one, the establishment is subject to COMAH. It is also clear that the inventories of all "installations" – including pipework – must be considered as a whole.

Extracts from COMAH Regulations [26] ***2(1) (definitions):***

"establishment" means the whole location under the control of an operator where a dangerous substance is present in one or more installations, including common or related infrastructures or activities, in a quantity equal to or in excess of the quantity listed in the entry for that substance in column 2 of Part 1 or in column 2 of Part 2 of Schedule 1, where applicable using the rule laid down in note 4 in Part 3 of that Schedule;

"presence of a dangerous substance" means the actual or anticipated presence of a dangerous substance in an establishment, or of a dangerous substance which it is <u>reasonable to foresee may be generated during loss of control</u> of the processes, including storage activities, in any installation within the establishment, in a quantity equal to or in excess of the qualifying quantity listed in the entry for that substance in column 2 of Part 1 or in column 2 of Part 2 of Schedule 1, and "where a dangerous substance is present" is to be construed accordingly;

Application to grid-scale BESS: The Regulations refer to "*a dangerous substance which it is reasonable to foresee may be generated during loss of control of the processes*". Both Flammable Gases (P2) and Acute Toxics (H1 and H2) are certainly "*reasonable to foresee*" in thermal runaway incidents which are now well-documented. The evolution of regulated, named and categorised hazardous substances from Li-ion battery cells in thermal runaway is also well-documented. A "worst credible accident" would have to consider that the entire inventory of Li-ion cells would be destroyed in a single BESS cabin at least. Cabin-to-cabin propagation should also be considered.

The Regulations apply to the entire "establishment", controlled by a single operator. Whilst the individual BESS compounds at Sunnica might be regarded as separate establishments, it is less reasonable that individual BESS cabins should be regarded as separate "establishments". They are separate "installations" but "establishment" means the entire area under control of an "operator".

Only if the most stringent safeguards were in place to ensure that the disastrous consequences of cabin-to-cabin propagation of "battery fires" could not conceivably occur, could it be argued that dangerous substances, exceeding the COMAH thresholds in quantity, were not "*reasonable to foresee* [being] *generated during loss of control of the process*".

We believe the COMAH regulations apply to BESS and that the approach of HSE is wrong in law.

Dangerous substances "reasonable to foresee … generated during loss of control of the processes": The literature and known experience of BESS accidents is clear that dangerous substances in the hazard categories H1 and H2 (Acute Toxic) and P2 (Flammable Gases) are foreseeable in the event of thermal runaway accidents. One of the Flammable Gases is Hydrogen, which is a "Named Dangerous Substance" in Part 2 of Schedule 1 of the COMAH Regulations 2015. Lower thresholds are specified for Hydrogen than for other P2 Inflammable Gases.

It remains therefore to consider the quantities of dangerous substances which could be generated if "control of the process is lost" in a thermal runaway incident. Published literature sources quantify evolution of flammable gases from tests of various Li-ion cells in sealed vessels. Open "fire tests" quantify the evolution of toxic gases particularly Hydrogen Fluoride. Many other test results exist in the records of specialist test laboratories, but here we rely upon two primary published sources.

Golubkov *et al.* (2014) [13] report quantities of evolved inflammables from Li-ion cells of three different electrode chemistries in thermal runaway situations. The proportion of Hydrogen (H_2), Methane (CH_4), Ethylene (C_2H_4) and Carbon Monoxide (CO) does not in fact vary greatly between different types of Li-ion cell, reflecting an underlying inventory of hydro-carbon material (plastics, electrolyte solvents etc) that remain similar in all Li-ion technologies. This is consistent with DNV/GL test data cited in the Hill/DNV report [8]. The quantitative estimates here are taken from results derived from cells with Nickel-Manganese-Cobalt (NMC) electrodes, as used in the McMicken BESS. It was not possible in the apparatus of Golubkov *et al.* to determine the concentrations of HF evolved.

Larsson *et al.* [11] report evolved quantities of Hydrogen Fluoride (HF) from Li-ion cells in open "fire tests", and also the Total Heat Released (THR) from combustion of the inflammables. Again these vary between cell technologies and "form factors", especially whether the cells have an outer metal cannister or are in the "pouch" format. Quantities between 20 – 200 mg / Wh are reported. The worst case figure is used in the following estimates; the lowest evolution reported for "pouch" cells was 43 mg/Wh.

Both sources report evolved gas quantities on a per Wh basis. We scale these to a Li-ion BESS cell size on the basis of stored energy since this will be roughly proportional to the electrolyte solvents and other polymer materials in the cell. Scaling on a per mass basis would be preferable, but this would require further information on the exact composition of the cells in the literature tests, and indeed those for the BESS in question. During the McMicken investigation, the cell manufacturers refused to release such data.

H1 and H2 Acute Toxics. The applicability of COMAH is easiest to determine in respect of Hydrogen Fluoride (HF). This has a dual hazard classification [12] as H1 Acute Toxic (skin exposure) and H2 Acute Toxic (inhalation) and both exposure routes would apply to the general public nearby. The lower tier COMAH threshold for H1 Acute Toxics is 5 tonnes [27]; using the upper estimate of 200 mg/Wh from Larsson, the BESS capacity at which a BESS enters the scope of COMAH (lower tier) is 25 MWh.

This is far below the projected storage capacities given in Table 3 (Appendix 1). With high storage capacity cabins (of e.g. 12.5 MWh), it would require propagation of a fire from just one cabin to a second, to generate HF above the COMAH threshold. It is not necessary to foresee a major conflagration involving multiple cabin-to-cabin propagation to bring the establishment within scope of COMAH; just two cabins would suffice. If 25 MWh were stored in a single large cabin, the question of cabin-to-cabin propagation is irrelevant.

The upper tier for “H1 Acute Toxics” is entered at four times higher capacity (100 MWh), which is well below the estimated capacity of Cleve Hill, and is also below *each* of the three Sunnica BESS compounds individually.

Even on the lowest evolution figure of 43 mg/Wh reported by Larsson *et al.* for “pouch” cells, the lower tier of COMAH is entered at a storage capacity of 120 MWh, again well within the “low case” capacity of each of the Sunnica BESS compounds, and Cleve Hill.

There is little doubt that either the lower or upper tier of COMAH is applicable to Cleve Hill and all three of the Sunnica BESS compounds, on the basis of “H1 Acute Toxics” (HF, skin route) alone.

Carbon Monoxide (CO) is categorised as an H2 Acute Toxic as well as a P2 Inflammable Gas, and will also be evolved, but in application of the aggregation rule its presence does not materially alter these conclusions. It is sufficient to consider HF alone.

P2 Inflammable Gases. Assessing applicability of COMAH on the basis of inflammable gases is more complicated because of the evolution of Hydrogen (H_2), Methane (CH_4), Ethylene (C_2H_4) and Carbon Monoxide (CO) in significant quantities, and because Hydrogen is a “named dangerous substance” for which different COMAH thresholds apply. These must be taken into account when applying the Aggregation Rule. Although proportions are generally similar, quantities do depend on the different electrode chemistries in the different Li-ion cell types.

Taking the largest evolutions reported by Golubkov *et al.* [13] for the LCO/NMC electrode type tested by them these are equivalent to 335 mg/Wh of P2 inflammables. For the NMC cells tested (the McMicken cells were NMC) the evolution was 214 mg/Wh. Taking the higher figure and applying the aggregation rule, grid-scale BESS enter the lower tier of COMAH at about 30 MWh capacity. Taking the lower figure, they enter the lower tier at 45 MWh capacity.

Hence there is little doubt that grid-scale BESS are lower tier COMAH establishments on the basis of “P2 Inflammable Gases” at storage capacities between 30 – 45 MWh.

Because of the variability between cell types, and the difficulty of scaling laboratory tests to actual BESS cells without detailed composition data, there is room for adjustment. However the calculated estimates of the thresholds for applicability of COMAH are so far below the projected capacities that it is inconceivable that the Cleve Hill and Sunnica BESS compounds would *not* be COMAH establishments, in lower tier at the very least, and probably the upper tier also.

Conclusion: Grid-scale Li-ion BESS should be considered COMAH establishments in the lower tier on the basis of “H1 Acute Toxics” (HF) alone, at energy storage capacities in the region of **25 MWh**. Upper tier would apply at about **100 MWh**. They should be lower-tier COMAH establishments on the basis of “P2 inflammable gases” alone, at storage capacities between **30 – 45 MWh**. Again larger establishments could become upper tier COMAH. Laboratory closed vessel and fire tests on actual Li-ion BESS cells proposed to be deployed would be required to refine these estimates definitively.

It is difficult to see how these conclusions could be avoided if tested in litigation.

Appendix 3: Shortcomings of Existing Engineering Standards for Li-ion BESS

The July 2020 report for the Arizona Public Service by Dr D Hill [8] provides a comprehensive discussion of existing engineering standards relating to BESS, and how they are *inadequate* to address the known hazards of "thermal runaway" incidents in Li-ion BESS. This was the failure mode leading to the explosion at McMicken, Arizona.

Unfortunately, when the UK's first "mega-scale" solar plant and battery storage site was granted approval in May 2020, this paper had not been published. The Cleve Hill solar developers cited one standard, UL 9540A [3]. This is also cited by some insurance and risk consultants [20].

It is important to be clear that nothing in UL 9540A addresses thermal runaway, and as a test method standard, it can provide no "safety certification" for Li-ion BESS.

Specific criticisms made in the Hill/DNV report include the following:

1. UL 1973 allows for the complete destruction of a BESS and the creation of an explosive atmosphere so long as no explosion or external flame is observed. An installation can do all these things but still "pass" UL 1973. At McMicken one rack was completely destroyed and an explosive atmosphere created but no flame or explosion occurred until first-responders opened the cabin door.
2. UL 9540A is merely a test method for generating data. It does not define any "pass/fail" criteria for interpreting results. Specifically, it does not address cell-to-cell cascading in thermal runaway, nor the evolution of a potentially explosive atmosphere. It does not even prescribe that the cell-to-cell cascading rate be measured.
   It allows that thermal runaway may proceed to an entire rack (as at McMicken) and offers testing of fire suppression systems (which operated correctly at McMicken but cannot prevent thermal runaway, and did not prevent an explosion).
   Presentation of data generated under UL 9540A to an "AHJ" (Authority Having Jurisdiction) does not translate to a succinct understanding of potential risks.
3. NFPA 855 [21] does require evaluation of thermal runaway in a single module, array or unit and does acknowledge the need for thermal runaway protection. However, it assigns that role to the Battery Management System (BMS). Yet thermal runaway is an electrochemical reaction that once started cannot be stopped electrically. It is uncontrollable by electronics or switchgear, only by water cooling.

The evolution of engineering and safety standards has not yet incorporated the lessons of experience arising from the McMicken explosion [8] **or explosion incidents in the UK like the Liverpool explosion and fire of 15 September 2020** [1]**. Compliance with existing standards does not prevent such incidents happening again.**

Articles in the industry press[3] do now recognise and discuss the problem of thermal runaway but make proposals such as: "*If off-gases can be detected and batteries shut down before thermal runaway can begin, it is possible that fire danger can be averted*".

Such statements betray a dangerous misunderstanding. Batteries cannot be "shut down", except by complete discharge, which cannot be done quickly. Taking cells "out of circuit" is useless; thermal breakdown and runaway will still occur.

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[3] [redacted]

Appendix 4 – Fire Safety Planning requirements in the Local Authorities' Joint Response to the Sunnica statutory consultation

This Appendix deals point by point with the BESS requirements in the Local Authority response (text in blue) pp 74 – 75.

Sunnica should produce a risk reduction strategy as the responsible person for the scheme as stated in the Regulatory Reform (Fire Safety) Order 2005. It is expected that safety measures and risk mitigation is developed in collaboration with services across both counties.

The Local Authorities require that the Fire Services work with Sunnica to prepare fire safety and risk mitigation measures. The Cambridgeshire and Suffolk Fire Services are therefore the only public bodies with independent oversight of BESS safety.

The use of batteries (including lithium-ion) as Energy Storage Systems (ESS) is a relatively new practice in the global renewable energy sector. As with all new and emerging practices within UK industry, the SFRS would like to work with the developers to better understand any risks that may be posed and develop strategies and procedures to mitigate these risks.

This paper is provided as input to this process, which appears to be insufficiently understood.

The promoter must ensure the risk of fire is minimised by:

- Procuring components and using construction techniques which comply with all relevant legislation.

This overlooks the points made in this paper that (i) existing legislation is being ignored by the statutory regulatory body, the HSE (ii) no adequate engineering standards exist to exercise Prevention measures over what is by now a very well-known hazard, viz. thermal runaway. Public Health and Safety cannot be assured whilst either of these situations continues.

- Developing an emergency response plan with both counties fire services to minimise the impact of an incident during construction, operation and decommissioning of the facility.
- Ensuring the BESS is located away from residential areas. Prevailing wind directions should be factored into the location of the BESS to minimise the impact of a fire involving lithium-ion batteries due to the toxic fumes produced.

This is impossible to satisfy. All the BESS compounds in the Sunnica proposal are sufficiently close to residential areas to present a major danger of toxic fumes in the event of an accident. Plume dispersal modelling should be performed to ensure that concentrations of HF cannot exceed dangerous thresholds in the event of the worst credible accident in a BESS compound.

- The emergency response plan should include details of the hazards associated with lithium-ion batteries, isolation of electrical sources to enable firefighting activities, measures to extinguish or cool batteries involved in fire, management of toxic or flammable gases, minimise the environmental impact of an incident, containment of fire water run-off, handling and responsibility for disposal of damaged batteries, establishment of regular onsite training exercises.

This requirement is very broad but insufficiently detailed. Means of cooling would require water volumes many times in excess of those requested. Management of inflammable gases is best addressed by venting, but that exacerbates the hazard of toxic gas plumes. Large water volumes may lead to unrealistic or impossible requirements for the containment, and subsequent disposal, of the contaminated water resulting from the fire-fighting activity. Other sections of this paper address these points.

- The emergency response plan should be maintained and regularly reviewed by Sunnica and any material changes notified to SFRS and CFRS.

- Environmental impact should include the prevention of ground contamination, water course pollution, and the release of toxic gases.

Preventing the release of toxic gases is all but impossible. A thermal runaway event WILL release toxic gases. If inflammables are vented to avoid /mitigate explosion risk, toxic gases WILL be vented. Ground contamination and water course pollution is almost certain to occur if sufficient water to control a major thermal runaway event is deployed. It will pose a significant challenge to contain, and safely dispose of, such large volumes of contaminated fire water.

The BESS facilities should be designed to provide:

- Automatic fire detection and suppression systems. Various types of suppression systems are available, but the Service's preferred system would be a water drenching system as fires involving Lithium-ion batteries have the potential for thermal runaway.

This is a correct precaution, but no specification is made of likely water volume requirements, nor for a "dry pipe" system allowing water to be deployed without cabin entry. We provide some water estimates elsewhere in this paper.

Other systems, such as inert gas, would be less effective in preventing reignition.

This is also a correct insight. The so-called "clean-agent" fire suppression system at McMicken was triggered correctly, but was useless to control thermal runaway. Moreover the stratified atmosphere created allowed the build-up of inflammables to a dangerous level, before the explosion occurred.

- Redundancy in the design to provide multiple layers of protection.
- Design measures to contain and restrict the spread of fire through the use of fire-resistant materials, and adequate separation between elements of the BESS.

This comment only vaguely considers the true essentials. The "elements of the BESS" could be: cells, modules, racks, strings, and the entire system. As discussed in the Hill/DNV report what is required is for the industry as a whole to accept that thermal runaway in an unacceptable hazard, and demand engineering standards that Prevent thermal runaway by design, or if it occurs, Prevent its cascade or escalation to larger system elements. This requires

a. Thermal barriers (i.e. Low thermal conductivity barriers, not merely refractory barriers, ideally with water cooling, between all cells, so that propagation from cell to cell cannot occur. This is precisely the requirement the industry has so far ***NOT*** made in the development of its engineering standards.
b. Separation of modules by similar barriers to Prevent module-to-module cascade.
c. Separation of Racks to prevent rack-to-rack cascade, even with ejection of molten metals.
d. Spacing of BESS cabins such that even with "75 foot flame lengths" cabin to cabin escalation is impossible. This is probably the most critical of all, since cabin-to-cabin escalation could turn a major fire incident into an unprecedented catastrophe, on the scale of the Beirut explosion or a small nuclear weapon.

- Provide adequate thermal barriers between switch gear and batteries,
- Install adequate ventilation or an air conditioning system to control the temperature. Ventilation is important since batteries will continue to generate flammable gas as long as they are hot. Also, carbon monoxide will be generated until the batteries are completely cooled through to their core.

This comment is very strange. There is no possibility whatsoever that air conditioning could be adequate "to control the temperature". The importance of ventilation is however recognised, as is the generation of carbon monoxide (toxic as well as inflammable). However the generation of Hydrogen Fluoride will also continue until the batteries are "completely cooled" and HF (H1 Acute Toxic by skin exposure) is much more toxic than CO (H2 Acute Toxic).

- Install a very early warning fire detection system, such as aspirating smoke detection.

The "very early warning" fire detection system required should be thermocouples to report continuously on the local temperature at every cell in the entire system. A single cell overheating can escalate via thermal runaway. By the time smoke is generated, this will be a "very late", rather than "very early" detection system. Just as thermal runaway events do not necessarily generate flame, neither do they necessarily generate smoke, until nearby combustibles are ignited.

- Install carbon monoxide (CO) detection within the BESS containers.

This is a good straightforward measure, but detectors for other gases expected (HF, H_2, CH_4) could equally well serve and multiple gas detection would provides additional security.

- Install sprinkler protection within BESS containers. The sprinkler system should be designed to adequately contain and extinguish a fire.

The excellent record of sprinkler systems in ordinary building fires shows they would help contain fire in regular combustible parts of the structure. However as discussed earlier in this paper, a mere sprinkler system would be useless to contain thermal runaway. Much larger water quantities would be needed.

- Ensure that sufficient water is available for manual firefighting. An external fire hydrant should be located in close proximity of the BESS containers. The water supply should be able to provide a minimum of 1,900 l/min for at least 2 hours. Further hydrants should be strategically located across the development. These should be tested and regularly serviced by the operator.

As discussed elsewhere, we believe these water requirements to be **under-specified by a factor of 100**, based on real experience with BEV fires. "Strategic location" is inadequate. Every single BESS cabin (potentially up to 150 of these at Sunnica East B alone) should have such a hydrant.

We remark elsewhere on the recommendation made by Hill/DNV for a "dry pipe" system to deploy water drenching inside via external connections, without cabin entry being needed.

- A safe access route for fire appliances to manoeuvre within the site (including turning circles). An alternative access point and approach route should be provided and maintained to enable appliances to approach from an up wind direction. Please note that SFRS requires a minimum carrying capacity for hardstanding for pumping/high reach appliances of 15/26 tonnes, not 12.5 tonnes as detailed in the Building Regulations 2000 Approved Document B, 2006 Edition, due to the specification of our appliances.

The requirement for safe access routes and space for appliances to manoeuvre could usefully be expanded into requirements for safe spacing of BESS cabins and thermal or flame barriers between cabins, to Prevent the "disaster scenario" of cabin-to-cabin propagation.

Final Comment: (over)

Final Comment:

The fundamental failure mode of Li-ion batteries presenting major hazard is thermal runaway. This paper is far from the first to identify the risk which is now well-known.

However the BESS industry as a whole has still not agreed or implemented adequate engineering standards to address basic Prevention measures to pre-empt thermal runaway accidents.

Until it does, Mitigation of major accidents by the Fire Services will remain the sole recourse for public protection and safety.