ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/352158070

Safety of Grid Scale Lithium-ion Battery Energy Storage Systems

Article · June 2021

CITATIONS
2

READS
25,410

2 authors:



Edmund John Fordham
Energetics Research and Consulting Limited
108 PUBLICATIONS **3,145** CITATIONS
SEE PROFILE



Wade William Magill Allison
University of Oxford
276 PUBLICATIONS **4,626** CITATIONS
SEE PROFILE

All content following this page was uploaded by Wade William Magill Allison on 05 June 2021.

The user has requested enhancement of the downloaded file.

Safety of Grid Scale Lithium-ion Battery Energy Storage Systems

EurIng Dr Edmund Fordham MA PhD CPhys CEng FInstP
Fellow of the Institute of Physics

Dr Wade Allison MA DPhil
Professor of Physics, Fellow of Keble College, Oxford University

Professor Sir David Melville CBE FInstP
Professor of Physics, former Vice-Chancellor, University of Kent

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

Executive Summary **p 2**

1. **Introduction** **p 4**
2. **Leading concerns** **p 10**
3. **Thermal runaway (Battery "fires")** **p 11**
4. **Toxic and flammable gas emissions** **p 14**
5. **Total energy release potential** **p 15**
6. **Applicability of the COMAH (Control of Major Accident Hazard) Regulations 2015** **p 17**
7. **Engineering standards for BESS** **p 18**
8. **Fire Safety Planning for BESS "fires"** **p 19**

References **p 22**

Appendix 1: Battery capacity calculations for grid-scale BESS at "Sunnica" **p 24**

Appendix 2: Applicability of the COMAH Regulations to large-scale BESS **p 26**

Appendix 3: Shortcomings of existing engineering standards for large-scale BESS **p 29**

Appendix 4: Fire Safety Planning in the Councils' Response **p 30**

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."

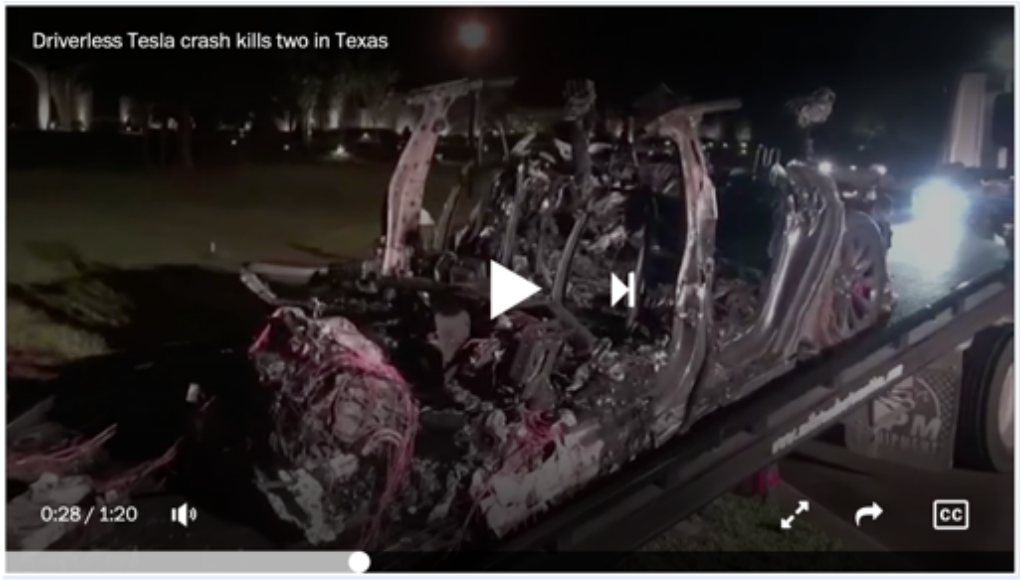
Location	Size	"Battery fire" cause	Time to bring under control	Water needed for cooling	Comments
Houston, Texas, April 2021	0.1 MWh	Driverless vehicle crash	4 hours	30,000 (US) gallons	Tesla Model S
South Korea	Various; 21 fires during 2018-19	Not known to Korean Ministry of Trade Industry and Energy	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)

[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.

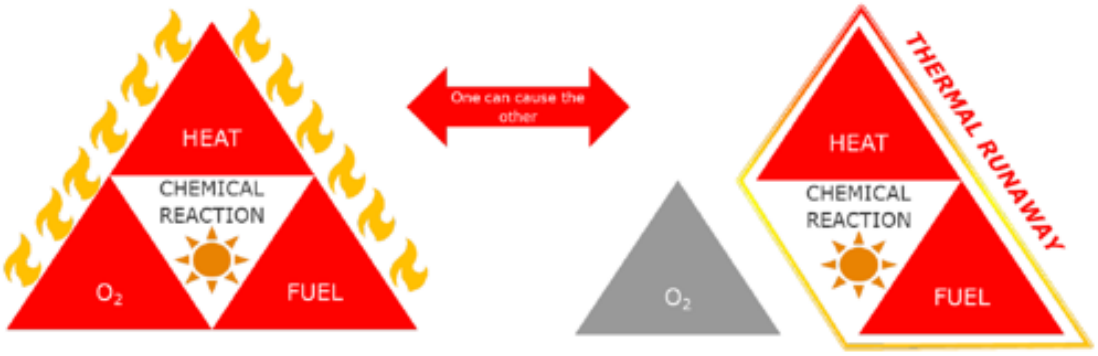


Figure 11 The fire triangle and its relationship to thermal runaway

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).

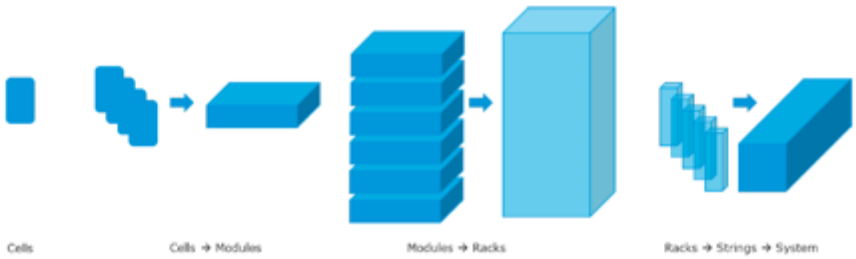


Figure 11: Cells stack into Modules; Modules into Racks; Racks into Strings; Strings into Systems.

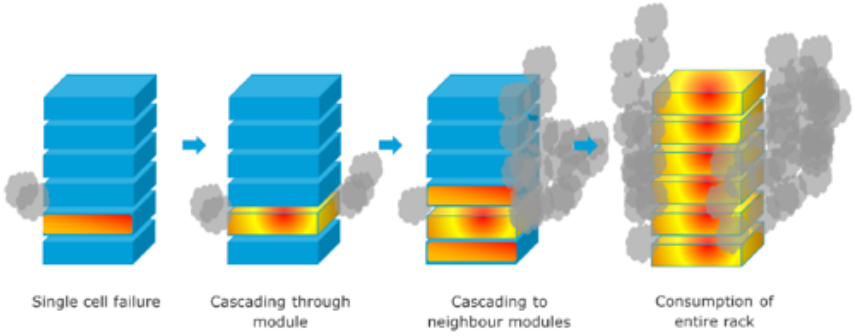


Figure 25 A single cell failure propagated through Module 2, then consumed the whole rack, releasing a large plume of explosive gases. This process could have occurred without visible flame, which would explain why the gases were not burned as they were emitted.

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 $\times$ 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

[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.

References

[1] Major Emergency Report MER 49652 (Liverpool City Council, Environmental Health Dept) Report from Merseyside Fire and Rescue Services and operator Ørsted into the battery fire at Carnegie Rd, Liverpool, 14-15 September 2020.
Promised January 2021 but still not released as of May 2021.
MER 49652 is a Liverpool City Council file code.

[2] Washington Post 19 April 2021
https://www.washingtonpost.com/nation/2021/04/19/tesla-texas-driverless-crash/

[3] Letter 2 August, 2019 from Commissioner Sandra Kennedy, of the Arizona Public Service Commission. Docket E-01345A-19-0076, State of Arizona Public Service Commission.

[4] Energy Storage News.
https://www.energy-storage.news/news/fire-at-20mw-uk-battery-storage-plant-in-liverpool

[5] Liverpool echo, 15 September 2020.
https://www.liverpoolecho.co.uk/news/liverpool-news/live-updates-fire-rips-through-18934842

[6] Cleve Hill Development Consent Order.
https://infrastructure.planninginspectorate.gov.uk/wp-content/ipc/uploads/projects/EN010085/EN010085-001957-200528%20EN010085%20CHSP%20Development%20Consent%20Order.pdf

[7] Sunnica Preliminary Environmental Information Report, Ch 3: Scheme Description

[8] D. Hill (2020). McMicken BESS event: Technical Analysis and Recommendations, Arizona Public Service. Technical support for APS related to McMicken thermal runaway and explosion."
Report by DNV-GL to Arizona Public Service, 18 July 2020. Document 10209302-HOU-R-01

[9] McKinnon, M B, DeCrane S, Kerber S (2020).
"Four fire-fighters injured in Lithium-ion Battery Energy Storage System explosion – Arizona".
Underwriters Laboratories report July 28, 2020.
UL Firefighter Safety Research Institute, Columbia, MD 20145

[10] Li-ion batteries video.
https://www.youtube.com/watch?v=CUgbmCSmSNY

[11] Larsson F, Andersson P, Blomqvist P, Mellander BE (2017).
Toxic fluoride gas emissions from lithium-ion battery fires.
Scientific Reports **7**, 10018 doi: 10.1038/s41598-017-09784-z

[12] Public Health England (2017).
Hydrogen Fluoride and Hydrofluoric acid – Incident Management, PHE gateway number 2014790

[13] Golubkov A W, Fuchs D, Wagner J *et al.* (2014).
Thermal runaway experiments on consumer Li-ion batteries with metal-oxide and olivin-type cathodes.
RSC Advances **4**, 3633-3642 doi: 10.1039/c3ra45748f

[14] D J C MacKay (2009) "Sustainable Energy – Without the Hot Air" UIT Cambridge Ltd p329

[15] Rigby S E, Lodge T J, Alotaibi S *et al.*
Preliminary yield estimation of the 2020 Beirut explosion using video footage from social media.
Shock Waves. doi:10.1007/s00193-020-00970-z

[16] Pilger, C, Hupe P, Gaebler P, Kalia A, Schneider F, Steinberg A , Henriette S & Ceranna L (2020). Yield estimation of the 2020 Beirut explosion using open access waveform and remote sensing data.
Bundesanstalt für Geowissenschaften und Rohstoffe - submitted https://doi.org/10.31223/X5W027

[17] Understanding COMAH – a Guide for new entrants
https://www.hse.gov.uk/comah/guidance/understanding-comah-new-entrants.pdf
Appendix 1 Figure 1 flowchart.

[18] Letter from Dr E J Fordham to HSE, 25 November 2020.
Addressed impersonally but sent Recorded Delivery and receipted.

[19] Letter from Ms Sarah Albon, Chief Executive of HSE, to Dr E J Fordham, 22 February 2021.

[20] Allianz Risk Consulting (2019) Battery Energy Storage Systems (BSS) using Li-ion batteries,
Technical Note Vol 26.

[21] National Fire Protection Association (2020)
Standard for the Installation of Stationary Energy Storage Systems Standard 855, Table 9.2

[22] Response of affected Local Authorities
(Cambridgeshire and Suffolk County Councils, West Suffolk and East Cambridgeshire District Councils) to Sunnica Consultation.
https://democracy.westsuffolk.gov.uk/documents/s39360/Sunnica%20Statutory%20Consultation%20Response.pdf

[23] Note (2/11/20) from Councillor Andrew Douch, Freckenham Parish Council, meeting 30 October 2020

[24] *Power Engineering,* 4/18/2017, "What you need to know about energy storage".

[25] Energy Institute (2019) Battery Storage Guidance Note 1: Battery Storage Planning, Sec 4.2 page 16

[26] A guide to the COMAH regulations (2015): https://www.hse.gov.uk/pubns/books/l111.htm

[27] A guide to the COMAH regulations (2015): https://www.hse.gov.uk/pubns/books/l111.htm
Schedule 1,Part 1, Col 2.

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 1.575 GWh 1.36 kilotons 2.72 "Beiruts"	3150 MWh 3.150 MWh 2.71 kilotons 5.44 "Beiruts"	Stored electrochemical energy only. Does not include chemical energy from inflammables.

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 reasonable to foresee may be generated during loss of control 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.

[3] https://www.energy-storage.news/blogs/preventing-thermal-runaway-in-lithium-ion-energy-storage-systems

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.

View publication stats