Department for
Business, Energy
& Industrial Strategy

Office for Product
Safety & Standards

Domestic Battery Energy Storage Systems

A review of safety risks

BEIS Research Paper Number 2020/037

September 2020

A report for the Office for Product Safety and Standards (OPSS) by Intertek

Acknowledgements

This independent research report was produced by Intertek.

The views expressed in this report are those of the authors, not necessarily those of the Office for Product Safety and Standards or the Department for Business, Energy & Industrial Strategy (nor do they reflect Government policy).

The following organisations were consulted as part of this project:

- American Fire Technologies (AFT)
- British Electrotechnical and Allied Manufacturers Association (BEAMA)
- Dupré Minerals
- Electrical Safety First (ESF)
- INERIS
- London Fire Brigade (LFB)
- Moixa Energy
- Powervault
- Siemens
- Tesla
- Varta

We are grateful to all respondents for their time and insights.

Contents

Executive summary

The application of batteries for domestic energy storage is not only an attractive ‘clean’ option to grid supplied electrical energy, but is on the verge of offering economic advantages to consumers, through maximising the use of renewable generation or by 3rd parties using the battery to provide grid services. Although the high cost of these systems has been a limiting factor in their growth, the growth in the Electric Vehicle (EV) market continues to drive down the price of modern lithium-ion (Li-ion) batteries, which is expected to further stimulate the market.

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. In response to this issue, this report was commissioned to take a broad look at potential failure mechanisms for domestic BESSs, the hazards related to a failure, risk mitigation and both existing safety standards and standards currently under development. **The report finds that if manufacturers and installers follow best industry practices and standards, they can significantly mitigate risks in the residential application of BESSs.**

- Part of this assessment involved interviewing stakeholders in order to better understand their concerns, capture their suggestions for improvements, and to address their questions. One particularly important perspective is that because the industry is at the early stages of BESS introduction, now is the time to consider all potential situations and how to do things correctly, to establish standards and guidelines which will not only apply now but also in the future when BESSs may be widespread and a part of everyday life.

Establishing technically sound, meaningful safety standards is critical to BESS success.

Based on a number of recent studies, the major lithium-ion battery fire characteristics can be summarized in the three hazard categories listed below:

- 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 gasses resulting from the rapid pressure build-up and vent release as the system heats up. Management of gasses generated must be considered in pack and system design.

- The toxicity of gasses generated from battery fires may require specific consideration in the design of ventilation systems.

There are many possibilities for risk mitigation on all levels from the cell to the system design and installation of the system. Many of the risks and requirements for mitigation are captured in the existing standards or standards under development. Below are some considerations regarding risk mitigation:

- 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 5kWh 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 safety requirements in UK for BESSs can be divided into electrical installation requirements, grid connectivity requirements, product safety regulation requirements and dangerous goods regulation requirements. The product safety involves several categories of safety standards such as: electrical energy storage systems, stationary lithium-ion batteries, lithium-ion cells, control and battery management systems, power electronic converter systems and inverters and electromagnetic compatibility (EMC).

Several standards that will be applicable for domestic lithium-ion battery storage are currently under development or have recently been published. The first edition of IEC 62933-5-2, which has recently been published, covers the safety of domestic energy storage systems. It will most likely be required in future versions of IEC 62933-5-2 that lithium-ion battery subsystems shall comply with BS EN 62619, IEC 62485-5 (under development) and IEC 63056. If these standards are developed with the intention of being harmonized standards under the low voltage directive or general product safety directive or referenced in other standards or regulations such as BS 7671, it would facilitate the clarity of the process for showing compliance with regulations. Current battery subsystems are often only tested to BS EN 62619.

Glossary

Term	Definition
Battery	Generally taken to be the Battery Pack which comprises Modules connected in series or parallel to provide the finished pack. For smaller systems, a battery may comprise combinations of cells only in series and parallel.
BESS	Battery Energy Storage System. Within the context of this document, this is taken to mean the product or equipment as placed on the market and will generally include the batteries, power conversion and control integrated within a single package.
BMS	Battery Management System. A protection mechanism built into a cell, pack or complete module to monitor and protect against fault conditions.
CAN	Controller Area Network. Enables microcontrollers and other electronic controls to communicate directly without the need for a host computer. Widely employed in the automotive sector and therefore battery technology.
Cell	A single unit comprising anode and cathode that converts chemical energy into electrical energy.
EMC	Electromagnetic Compatibility – the ability of a device to be able to operate within its intended environment without being affected or causing effect to other devices.
EN	European Norm. A standard developed by a European Standardisation Body that provides the basis for evaluation of equipment.
EV	Electric Vehicle.
Grid connected	Any power generation equipment which is connected directly to the public electrical supply with the purpose of providing distributed generation.
HF	Hydrofluoric Acid. A by-product of a Li-ion Battery Fire. Corrosive and acutely toxic.
HMI	Human-Machine Interface – general term used to describe the controls and display by which the operator interacts and controls equipment.
HRR	Heat Release Rate. Describes the rate of heat generation in a fire and is stated in Joules per second or Watts. It is a key factor in determining fire hazard and risk.
ICE	Internal Combustion Engine.

IEC	International Electrotechnical Commission. An International standardisation body.
IET	Institute of Engineering and Technology. UK based Professional Body. Develops Codes of Practice and Guidance documents and maintains the UK Wiring Regulations.
IGBT	Insulated-Gate Bipolar Transistor.
Inverter	Part of the Power Conversion Equipment that converts the DC provided by the battery into AC suitable for supply to the load and the grid. For battery applications inverters are b-directional allowing control of both charging and discharging.
Li-ion	A broad range of rechargeable cell chemistries based on Lithium-Ion technology. Lithium ions move through an electrolyte between a negative and positive electrode. The process is reversible to allow for charge and discharge.
MCB	Miniature Circuit Breaker. A resettable overload protection device incorporated as part of an electrical installation.
MCCB	Moulded Case Circuit Breaker. A resettable overload protection device incorporated as part of an electrical installation. For higher current applications than an MCB.
Module	Modules comprise several cells connected in series or parallel. This is a subsystem of the Battery or Battery Pack
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor.
OEM	Original Equipment Manufacturer.
PCE	Power Conversion Equipment. Term commonly used to describe all equipment related to power conversion and grid connection.
PCS	Power Conversion Subsystem. Describes all equipment downstream of the battery providing power conversion and protection for the load.
PV	Photo-voltaic. The term used to describe the energy generating mechanism that converts light into electrical energy.
RCBO	Residual Current Breaker with Overcurrent. Similar to Miniature Circuit Breaker but incorporates detection for residual current that may create a hazard as a result of an earth fault. A resettable overload protection device incorporated as part of an electrical installation.
SOC	State of Charge. The state of charge of the battery relative to the capacity.

1 Introduction

The application of batteries for domestic energy storage is not only an attractive ‘clean’ option to grid supplied electrical energy, but is on the verge of offering economic advantages to consumers, through maximising the use of renewable generation or by 3rd parties using the battery to provide grid services.

Even though few incidents with domestic BESSs are known in the public domain, the use of large batteries in the domestic environment represents a safety hazard. This report undertakes a review of the technology and its application, in order to understand what further measures might be required to mitigate the risks. The focus is on lithium-ion battery technology, as this now dominates new designs of BESS.

The study starts with a description of the operation of BESS systems, the market, and a review of the published data on battery fires. It then considers in detail how lithium-ion batteries can fail, and the mitigating measures such as best practice in BESS design and installation that can reduce the risk or impact of failure. Appendix 2 gives a comprehensive review of current safety standards and codes relating to domestic BESSs.

Fortunately, there have been few recorded fires involving domestic lithium-ion battery storage systems so this report includes experience of Li-ion battery fires in other applications. The causes and effects of thermal runaway, rapid pressure build-up and toxicity of gases are also considered.

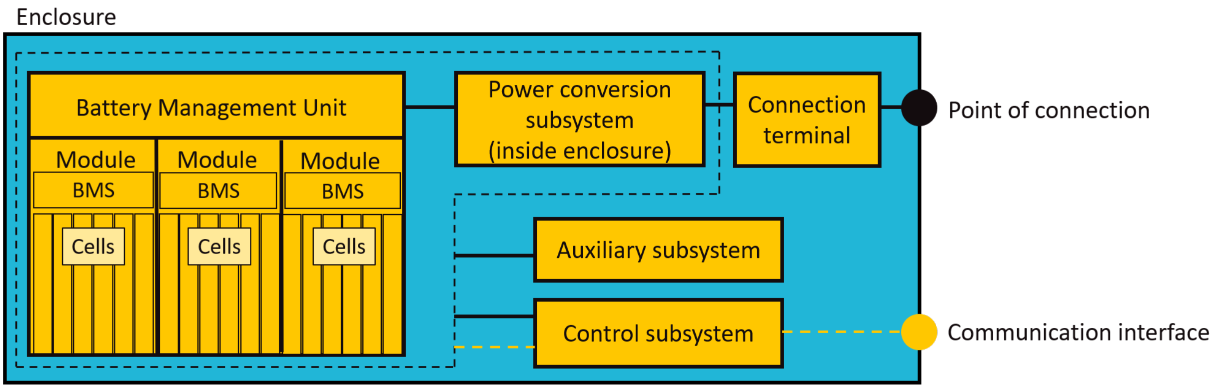
The desk research was supplemented by 1:1 interviews and a discussion meeting with sector experts, listed in the acknowledgements.

2 The battery energy storage system

2.1 High level design of BESSs

A domestic battery energy storage system (BESS), usually consists of the following parts: battery subsystem, enclosure, power conversion subsystem, control subsystem, auxiliary subsystem and connection terminal (Figure 1).

Figure 1: Simplified sketch of components within a domestic BESS



2.2 Power conversion subsystem

The power conversion subsystem (PCS) plays a critical role in the transfer of energy to and from the electrical supply. It includes an inverter/charger, which is usually a single bidirectional design, but occasionally might be separate components. When charging the battery, it draws current from the AC supply (point of connection) and converts it to a DC current. When exporting power to the public supply grid or for local 'self-supply', the inverter converts the DC source provided by the battery subsystem into an AC supply.

Domestic BESSs currently available on the market can be one of three types:

- Using 'off-the-shelf' bi-directional inverters
- Using proprietary designed inverters or adapted commercial products
- Units that are supplied as 'storage only' and require the installer, systems integrator or end user to provide a suitable power converter.

The charger/inverter may manage the power to and from the energy storage system alone, or may integrate other localised renewable energy sources, most commonly photovoltaic solar systems.

2.3 Auxiliary subsystem

The auxiliary subsystem includes all necessary equipment intended to perform BESS system auxiliary functions such as heating, ventilation, fire suppression and air conditioning systems.

2.4 Control subsystem

The control subsystem is used for monitoring and controlling the BESS system. It may include a communication subsystem, protection subsystem and management subsystem.

2.5 Battery subsystem

The battery subsystem consists of a battery management system (BMS) and cells that can be divided into several modules.

The cells need to be kept within their specification regarding voltage, temperature and current for safe operation, and therefore require a battery management system (BMS). For larger systems there is often a separate BMS operating at different levels, e.g. one BMS at module level and one at pack level. The BMS is a critical part of the complete safety system, and in addition there is hardware protection.

Many factors must be considered in the design of safe, robust battery subsystems. The design and engineering of the battery management system (BMS) is a safety critical concern. The BMS is at the heart of a battery's safe operation. Properly designed, the BMS will provide early detection of potential problems and take actions to mitigate the potential consequences.

3 Battery technologies

Table 1 below displays characteristics of the two battery chemistries, Lead-acid and Li-ion, that are most commonly used in domestic BESSs today.

Table 1: Characteristics of lead-acid batteries versus lithium-ion batteries

<table>
<tr><th>Type</th><th>Energy Density Wh/kg</th><th>Voltage V</th><th>Electrolyte</th><th>Usage</th><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td rowspan="2">Lead-acid</td><td>< 40</td><td>2</td><td>Sulphuric acid</td><td rowspan="2">Mass production for SLI, UPS, stationary, fork lift trucks.</td><td rowspan="2">Cost effective
Mature technology
Power capability at low temperature.</td><td rowspan="2">Low energy density
(high maintenance)
Life at elevated temperature
Hazardous materials.</td></tr>
<tr><td colspan="3">There are different types: Open, SMF (sealed maintenance free), VRLA – AGM or Gel-type.</td></tr>
<tr><td rowspan="2">Li-ion</td><td>100-260</td><td>3.2-3.8</td><td>Organic solvent</td><td rowspan="2">Mass production for portable, stationary, industrial and HEV/EV applications.</td><td rowspan="2">High energy & power
Cycle life
Wh efficiency.</td><td rowspan="2">Cost
Safety
Maturity (large format)
Temperature range.</td></tr>
<tr><td colspan="3">Family of chemistries resulting in different properties. Most common; LCO, NMC, LFP.</td></tr>
</table>

The battery technology used in domestic BESSs can vary but most systems on the market today for domestic battery energy storage are of lithium-ion type. However, valve regulated lead-acid batteries have traditionally been dominant and are still used in many installed systems. The main disadvantage of lead acid for this application is their limited lifetimes when charged/deep discharged. Therefore, they are not normally used in domestic storage.

Lead-acid batteries are therefore not covered further in this report.

3.1 Lithium-ion chemistry

Lithium-ion technology comprises a family of different chemistries in which the main reaction is the transport and intercalation of lithium ions into the cathode and anode respectively. The most common anode (negative) material is graphite but there are alternatives with hard carbon and titanate. Both hard carbon and especially titanate give better power capability and cycle life, but at the cost of energy content. The cathode material is often a metal oxide and some of the most common cathode types are, NMC (lithiated nickel manganese cobalt oxide), NCA (lithiated nickel cobalt aluminum oxide), LCO (lithiated cobalt oxide) and LFP (lithiated iron phosphate). They all have slightly different features but LFP has a lower voltage and therefore a lower energy density than the other chemistries.

The anode and cathode are separated by a porous film, the separator, that often consists of several layers of polymers. Electrode and separator are soaked in an electrolyte that provides the lithium ion transport between the electrodes. The electrolyte consists of organic solvents with dissolved lithium salt (LiPF6).

Jelly roll with anode, separator, cathode and separator (left to right) in the picture (© Intertek).

3.1.1 Lithium-ion cell

There are three different form factors of cells: cylindrical, pouch cells, and prismatic. The electrodes could either be stacked or rolled into a jelly roll that may also be flattened. The cells are sealed, and no venting should occur under normal operation.

Cylindrical cell Pouch cell Prismatic cell

Different form factors for lithium-ion cells (© Intertek).

The cells are connected in series and parallel in order to increase voltage and capacity respectively. For larger battery packs, the cells are often grouped into sub-packs called modules. The modules could then be connected in series or in parallel to form the complete battery pack.

Cell manufacture and battery construction can be quite complex. Application of existing battery and system standards address performance and safety, and although they undergo continuous review and improvement, they do not completely address the full range of complexities involving battery design and manufacture, and so there are occasional cell failures. Modest changes in chemistry or construction could have severe consequences. For perspective, one should keep in mind that there are billions of cells in the marketplace, so the incident rate is actually quite low, of the order of one in a million or perhaps as low as one in 10 million [1].

4 Review of the domestic energy storage market

There are a number of BESS for domestic use on the UK market both from UK and large global suppliers. An increased number of suppliers is expected during the coming years. The price for a battery energy storage system can vary substantially. According to the webpage Solarguide [2], the battery price can range from £500 to well over £10,000, excluding the cost of having it fitted. A general average for the price (excluding installation costs) could be around £1,000 per kWh. The installation charges could be from at least £500 up to £2,000+ depending on the complexity of the system. Some systems include the inverter whereas it may have to be added for others at a cost around £1,000.

4.1 Example of BESS Installations

The following are two examples of BESS installations. Note that neither are located inside a living area.

Varta-Storage ‘Pulse’, garage installation (© Varta Storage GmbH).

Tesla ‘Powerwall’, outdoor wall installation (© Tesla).

4.2 Examples of domestic BESS products on the UK market

Examples of products that can be found on the UK market are shown in Table 2. This summarises information found on each manufacturer’s webpage. The systems have a useable energy content varying between 2.5 and 25.2 kWh. The nominal voltage of the battery modules is generally around 50 V but there are some systems with higher nominal voltage. The nominal energy of each battery module could not be found for each system. Nevertheless, the values that were found vary between 1 kWh and 6.3 kWh. The chemistries of the cells are often Lithium Nickel Manganese Cobalt Oxide (NMC) or Lithium Iron Phosphate ($LiFePO_4$).

The products are all CE marked. A common battery safety standard that battery modules are tested to is IEC 62619. For the inverters, IEC 62109-1 and IEC 62109-2 are commonly used safety standards. Many systems have also been certified for the North American market according to standards such as UL 1973 (battery modules) and UL 1741 (inverter). Specifically, for the UK market, the inverters need to comply with the engineering recommendations G.83/2 (G98) and G.59/3 (G99) as well. Applicable standards for domestic BESS are summarized in section 7 and Appendix 1.

Table 2: Examples of domestic battery energy storage products available in UK

Manufacturer	System	Chemistry	Charge/discharge power	Useable energy (System)	Nominal voltage of battery system	Nominal energy of battery module	Nominal voltage of battery module	IP RATING	CE-mark	battery Safety standards	Inverter/SYSYEM Safety standards
Duracell	Energy Bank DURA3EBV1	LiFePO4	3.3 kW/ 3.3 kW	3.3 kWh	52 V	not found	not found	IP 32	Yes	IEC 62619	EN 62477-1 EN 62109-1 EN 62109-2 EN 62040 G 83 VDE 4105 VDE 0126-1-1
LG Chem	RESU (only battery)	not found	3.0/3.0 kW, 4.2/4.2 kW, 5.0/5.0 kW	3.3-13.1 kWh	51.8 V	3.3 kWh	51.8 V	IP 55	Yes	IEC 62619 and UL 1973	N/A
LG Chem	RESU7H (only battery)	not found	3.5/3.5 kW	6.6 kWh	400 V 490 V	not found	not found	IP 55	Yes	IEC 62619	N/A
LG Chem	RESU10H (only battery)	not found	5.0/5.0 kW	9.3 kWh	400 V 490 V	not found	not found	IP 55	Yes	IEC 62619 and UL 1973	N/A
Moixa	Moixa Smart Battery (only battery)	LiFePO4	0.7/0.5 kW	2 kWh 3 kWh	50 V	1 kWh 1.5 kWh	25 V	not found	Yes	EN 60950-1	N/A

Powervault	Powervault 3	Lithium polymer: Li-NMC	3,3/5,5 kW	4.1 - 20.5 kWh	48 V	2.05 kWh	48 V	IP 41	Yes	not found	G.83/2 and G.59/3
SolaX	Triple Power T45 (only battery)	not found	2.5/2.5 kW	4.5 - 18 kWh	100.8 - 403.6 V	4.5 kWh	101 V	IP 55	Yes	IEC 62619 and UL 1973	N/A
SolaX	Triple Power T63 (only battery)	not found	2.5 / 2.5 kW	6.3 - 25.2 kWh	100.8 - 403.6 V	6.3 kWh	101 V	IP 55	Yes	IEC 62619 and UL 1973	N/A
Sonnen	sonnenBatterie hybrid 9.53	LiFePO4	3.3/3.3 kW	5-15 kWh	48 V	2.25 kWh	48 V	IP 30	Yes	IEC 62619	IEC 62109-1 IEC 62109-2 G.83/2 and G.59/3
Tesla	Powerwall 2 AC	not found	3.68/5 kW	13.5 kWh	50 V	not found	not found	IP 67 (battery and power electronics) IP 56 (wiring compartment)	Yes	IEC 62619 and UL 1973	IEC 62109-1 IEC 62109-2 UL 1742
VARTA	Element	NMC	2.2/1.8 kW, 3.4/3.0 kW 4.0/3.7 kW	6.5 - 13 kWh	not found	not found	not found	IP 22	Yes	not found	DIN EN 62109-1 G.83/2 and G.59/3
VARTA	Pulse	NMC	1.8 / 1.6 kW, 2.5 / 2.3 kW	3.3-6.5 kWh	not found	not found	not found	IP 33	Yes	not found	DIN EN 62109-1 G.83/2 and G.59/3

5 Fire statistics

The number of installed units of domestic lithium-ion battery energy storage is still limited and there are currently no specific statistics for fires involving these systems. However, even though few incidents with domestic battery energy storage systems (BESSs) are known in the public domain, questions have been raised regarding the safety of these systems. The concern is based on the large energy content within these systems.

5.1 Large fixed and small portable battery systems

Most of the available fire statistics for lithium-ion batteries are related to smaller portable products. The associated risks are different in many aspects between a large fixed installed system and a smaller portable product with battery and it could therefore be difficult to relate the statistics between the two product types. Below are some general characteristics of small format batteries used in consumer electronics versus large format batteries used in domestic energy storage systems.

5.1.1 Small format batteries (consumer electronics)

- Portable products may be exposed to mechanical abuse as well as a large variation in environmental conditions that could increase the risk for internal cell faults.
- The location of the portable device cannot be controlled, it could be in a pocket, bed etc. surrounded by combustible material.
- The battery may be interchangeable, which increases the risk that counterfeit batteries are used. There is also an increased risk that various chargers may be used and not the charger specified for the product.
- Less energy and lower chemical content than a larger battery, resulting in less heat and gases in the event of a fire.
- Extreme cost sensitivity drives manufacturers to consider the use of less expensive components.

5.1.2 Large format batteries (domestic energy storage)

- This format usually entails fixed installation for which the location may be chosen and possibly also regulated.
- Larger amount of energy and chemical mass compared to a smaller battery which can result in more heat and gasses in the event of a fire.
- An internal short and temperature increase in one cell could result in a propagation where the fire is spread to the entire pack.
- With stationary battery packs, a larger size could enable better possibilities for designing the pack to avoid propagation of fire between cells through greater spacing and insulation between cells and modules.

- In some designs, battery modules may be field replaceable.

5.2 Reported battery-related fires in London

Table 3 below shows the number of fires for which batteries have been the likely cause of fire found in the London fire brigade's (LFB) database during a ten-year period. Smaller incidents are not likely to have been recorded and the number of fires is therefore likely to be underestimated. The data is expected to be mainly related to batteries in portable consumer products (as these are mainly lithium-ion batteries). The difference in number of incidents before 2011 and after is believed to be as a result of changes in reporting. After 2011 the number of incidents has been on a fairly constant level, whereas the number of products sold with lithium-ion has increased significantly during the same period.

Table 3: Statistics from the London fire brigade with yearly reported fires in which batteries have been considered the likely cause of the fire

Calendar year	Batteries, generators	Battery charger	Total
2009	252	4	256
2010	256	5	261
2011	265	5	270
2012	161	7	168
2013	142	4	146
2014	142	6	148
2015	146	8	154
2016	155	10	165
2017	150	16	166
2018	162	9	171
Grand total	1831	74	1905

5.3 E-cigarettes in US

E-cigarettes and Hover boards are two other consumer products are known to have caused numerous fires during recent years due to lithium-ion batteries, and for which specific efforts have been made to understand and mitigate the risks. The statistics show that there is a strong correlation between E-cigarettes sold and the number of incidents in the US [3]. Of the 291 reported fires, 10 resulted in major fires whereas 91 in minor fires. Smaller fires are not likely to have been reported. The incidents often occurred when the device concerned was in a pocket or in use, and the user was therefore able to take action while the fires were still small.

5.4 Lithium-ion battery fires during air transport

Lithium-ion battery fires during air transport are an area of focus where there are requirements to report incidents. The Federal Aviation Administration (FAA) has a list of battery-related incidents associated with aircraft transport resulting in fire, smoke, explosion or significant heat dating from March 1991 to February 2019 [4]. A similar list also exists for the UN Subcommittee of Experts on the Transport of Dangerous Goods and by the ICAO Dangerous Goods Panel. In the list from FAA mechanical abuse and external short circuit are two common causes for battery fires in lithium-ion battery containing packages for Air Cargo. For personal transported batteries, cell internal fault is often suggested as the cause for the fire, but incorrectly packed spare batteries that short circuit during transport is another cause for some of the fires. The yearly number of transported cells and batteries have been estimated to be in the region of several billions.

5.5 Fires in PV installations by nation

5.5.1 UK

Due to a rapid increase in installed photovoltaic (PV) systems in UK, there are several media reports of fires in PV installations. A project was initiated in 2015 in which Building Research Establishment Ltd. (BRE) National Solar Centre (NSC) and BRE Global Fire Safety Group collected information about PV fires to feed information to industry standards and fire and rescue services [5]. According to the study there were about 900,000 PV installations in UK by the end of 2016. About 50 fires related to PV systems were found in a review of open sources up to January 2017, of which 17 resulted in serious fires. Fires are classed as serious if they were difficult to extinguish and spread beyond the area of origin. About half of them were in domestic buildings whereas the others were in non-domestic buildings and some in solar farms. The root cause is known for about 50 % of the examined fires. The most common known root cause was poor installation often associated with outdoor installation and water intrusion. It is not stated in the report if lithium-ion batteries were used in any of the installations.

5.5.2 Australia

Australia has also had a rapid increase in PV installations and experienced 400 fires between 2009 and 2015 [6]. The number of fires correlates with the number of systems installed. Incorrect installation was often believed to be the cause of the majority of these fires. Current installations are predominantly lead acid but lithium-ion batteries are expected to take over. Two to three out of 400 fires in total were assumed to have been caused by the battery, although it is not known what proportion of these involved a BESS.

5.5.3 US

In the report, Fire Hazard Assessment of Lithium Ion Battery Energy Storage Systems prepared for Fire Protection Research Foundation in 2016, one incident was reported that involved lithium-ion batteries in a solar energy facility in Arizona. There were no other public reported fire incidents in

US where the BESS was identified as having started the fire [7]. However up to that date, the major part of the installations have been lead acid batteries.

5.5.4 Germany

Two incidents of domestic BESSs were found in open access literature that had been reported in Germany [8]. The reported incidents involved fire in domestic lithium-ion battery storage, used in combination with PV installations. No-one was injured in the incidents, but the damage costs were 12,000 and 25,000 EUR respectively. For one of the batteries, using pouch cells, the failure cause was listed as technical defect (explosion), but for the other one no failure cause was listed.

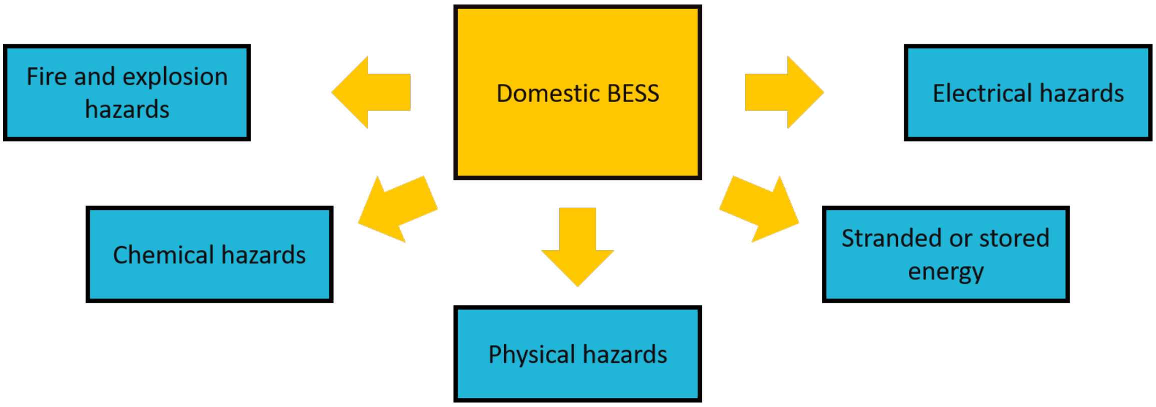
5.6 Summary

It can be seen from the fire statistics reviewed, covering different products with lithium-ion batteries, that the root cause varies significantly. For the incidents where a root cause has been identified, it is often related to some type of abuse where the lithium-ion cell has been exposed to conditions outside specifications. Cell internal faults have also been mentioned as the root cause for a number of incidents in carry on batteries in aircraft. Standards for lithium-ion cells and batteries, specify requirements and tests for the safe operation under intended use and reasonably foreseeable misuse. Mechanical and electrical abuse can be simulated in a test laboratory and be part of a standard. However, it is more difficult to simulate cell internal faults. Instead, these must be controlled by a requirement for quality control of the cell manufacturing processes. Since it is difficult to have complete control, one could assume that a cell internal fault may occur and that the consequence of the faults should be handled and minimized on a system level.

6 Failure characteristics specific to lithium-ion batteries

The hazards for a domestic battery energy storage system (BESS) could be summarized in the following categories (shown below): fire and explosion hazards, chemical hazards, electrical hazards, stranded or stored energy and physical hazards. A description of these hazards can be found in Appendix 1.

Figure 2: Potential hazards with domestic battery energy storage

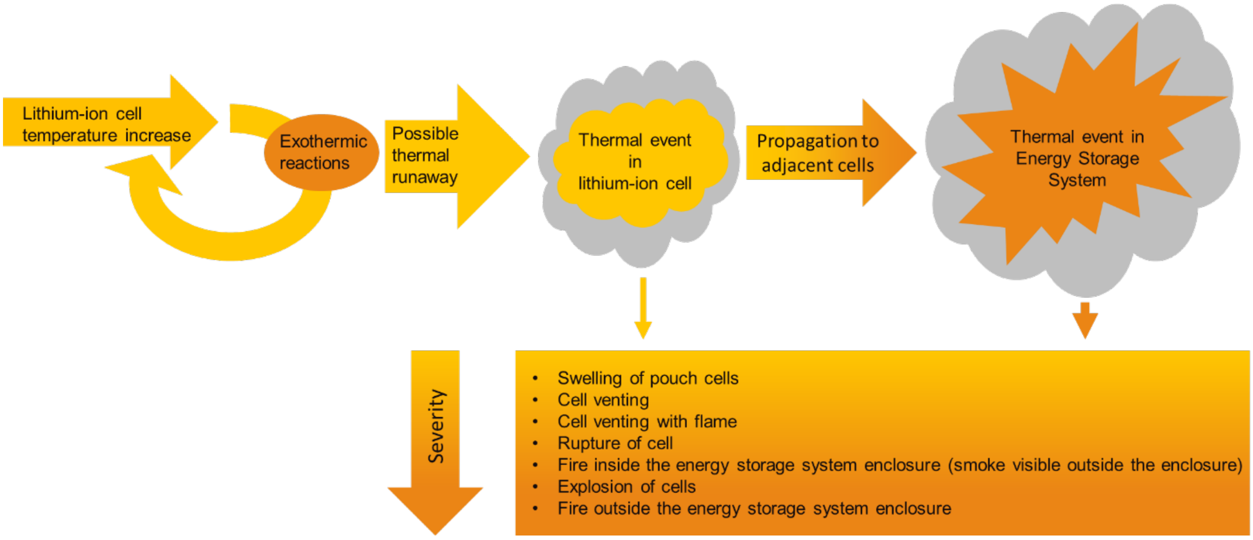


The main critical component in a domestic battery energy storage system (BESS), and the component that is the cause for many of these hazards, is the lithium-ion cells themselves. Lithium-ion cells must be kept within the manufacturer's specifications for the operating window regarding current, temperature and voltage. Outside this operating window, unwanted reactions occur that could cause defects that either directly, or after continued operation, may lead to unsafe conditions such as, release of gases, fire etc. At elevated temperatures, the decomposition of electrodes and electrolyte can result in an escalating behaviour called thermal runaway.

Thermal runaway is initiated by a failure event that causes a temperature increase, either locally within the cell or generally for the whole cell. The anode, electrolyte and cathode materials begin to decompose and exothermic reactions within the cell release additional heat. Once thermal runaway has started, a rapid (exponential) increase in cell temperature and pressure occurs. The exponential increase in temperature and pressure may lead to venting of flammable electrolyte and possibly flames or a violent rupture of the cell during which cell content may be ejected. Depending on battery design, the event can cascade to the adjacent cells in the battery pack resulting in fire or explosion of the entire BESS.

The nature of a thermal runaway within a cell and the spread into the entire pack is shown in Figure 3.

Figure 3: Description of a thermal event in a lithium-ion cell leading to fire or explosion of the entire BESS



All Li chemistries are susceptible to catastrophic failures and need active safety precautions. In addition to energy release (heat, fire, explosion), Li-ion cells emit hazardous substances when they rupture. Vented gases and electrolyte solvents from Li-ion cells are flammable, some are toxic and some are immediately reactive. Lithium hexafluorophosphate ($LiPF_6$) salt in the electrolyte reacts with humidity to form hydrofluoric acid (HF), an extremely strong acid with etching qualities and known to cause human tissue damage and breathing difficulty. Hydrocarbons, CO and CO_2 are also formed. The temperature and state of charge (SOC) at failure are some of the parameters that affect the composition of the gas.

Even though much focus is given to the worst outcome of a failure such as fire and explosion, there are several other potential outcomes during a failure of a lithium-ion cell, such as deformation, rupture, leakage, heating, venting, smoking, fire (flames), explosion and non-functional cell(s). These outcomes could also constitute a hazard and could, with time and especially as part of a larger system, lead to a greater hazard. A list with definition of the different outcomes as a response to abuse test could be found in the standard IEC 62660-2 “Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 2: Reliability and abuse testing” and is shown in Table 4 below. The potential outcomes are related to each other and several outcomes may occur during a failure.

In the mandatory standardised safety tests, the test sample is generally exposed to various normal and abnormal abusive conditions with the requirement of no fire and no explosion in order to pass. The introduction of larger lithium-ion batteries has led to an increased interest in understanding implications of battery fires and have resulted in a number of fire studies for applications such as electric vehicles, stationary energy storage systems, etc.

Table 4: Description of battery hazards from IEC 62660-2 [9]

Hazard/Outcome	Description
No effect	No change in appearance.
Deformation	Change or deformation in appearance including swelling.
Venting	Escape of liquid electrolyte from vent or venting with mist release.
Leakage	Visible escape of liquid electrolyte from a part except vent, such as casing, sealing part and/or terminals.
Smoking	Release of fumes, including possible soot particles, from vent.
Heating	Temperature increase of the exterior of the battery.
Rupture	Mechanical failure of a cell container case induced by an internal or external cause, resulting in exposure or spillage but not ejection of materials.
Fire	Emission of flames from a cell or cell block for more than 1 s.
Explosion	Failure that occurs when a cell container opens violently, and major components are forcibly expelled.

6.1 Heat release

The characteristics of lithium-ion battery fires are unique and are dependent on the type and nature of the installation. The complexities of battery fires are discussed in the following sections.

The total combustion energy has been measured in several lab tests under various conditions. The Advanced Rechargeable & Lithium Batteries Association (RECHARGE) has gathered data from published fire tests and analysed the data from different perspectives [10]. The total heat released during total combustion of lithium-ion batteries ranged from 30 to 50 kJ/Wh, or 4 to 10 MJ/kg, which the Association says is about 5-10 times less than for organic materials like plastic or paper.

The Fire Protection Research Foundation has initiated several studies in order to understand fire hazards of lithium-ion batteries in storage. In those studies, the batteries or cells are stored within their typical packaging, i.e. cardboard boxes and plastic material inside separating the units. They found that the heat release rate (HRR) was similar for packaged lithium-ion batteries and cartoned unexpanded plastic (CUP) in fire tests using external fire as ignition [11]. Packaging containing densely packed Li-ion cells and minimal plastics (cylindrical cells and small pouch cells) exhibited a delay in the involvement of cells in the fire. Packaging containing significant quantity of loosely packed plastic (i.e. power tool packs, CUP and larger pouch cells packed with more plastic material), exhibited a rapid increase in energy release due to the plastic fire [11].

Comparison of fire tests of internal combustion engine (ICE) vehicles with battery electric vehicles (BEV) has shown that the HRR is similar for both types of vehicle and that the battery does not constitute a significant part of the HRR [12] [13]. However, the EV fire still needed more water in order to be extinguished compared to the ICE car fire.

In the summary made by RECHARGE, the HRR for cells/batteries of 10 Wh size varied from 10 to almost 1,000 kW with a maximum value of HRR of 1,000 kW/kg battery revealing a large variation in the rate [10].

For larger battery packs, the design of the pack may mitigate and delay spreading fire from one part or cell to another. If the battery is designed without cascading protections, there is a risk that a fire is assumed to be extinguished but latent, residual heat slowly creates a delayed cascading of fire where transferred heat reinitiates the fire. This was observed in tests performed by DNV-GL reported in their study for NYSERDA and Consolidated Edison “Considerations for ESS fire safety” [14]. DNV-GL replicated this effect in a lab test where they measured temperatures up to 300°C higher inside the pack between the cells than at the exterior of a pack while extinguishing the pack fire. To be effective, extinguishing media must reach the cells themselves which can be difficult if the battery enclosure is designed to contain an internal initiated fire [14].

The effect of reignition of a battery fire was also observed in Exponent’s tests with lap top batteries where a suppressed fire was reignited due to cells undergoing thermal runaway about 20 minutes after the flames from the first fire had been extinguished [15].

The potential to increase safety by good design was shown in fire tests of energy racks with 100 kWh lithium-ion cells made by Exponent for the Fire Protection Research Foundation. It was shown that no propagation occurred when thermal runaway was initiated internally, the fire was limited to one module and the risk of spreading the fire was minimal if the recommended safety distances for installation were used [7].

The propagation behaviour of the fire in larger battery packs was also captured in the summary by RECHARGE. It was found that the maximum HRR per kg of batteries was decreasing for larger batteries because not all of the cells were reacting together at the same time [10].

The HRR is also dependent on SOC of the cell with higher SOC resulting in higher HRR [14] [16]. Different cells and chemistries do also show large variation in HRR. In the study by DNV-GL it was found that cells with $LiFePO_4$ and Titanate had a lower HRR and lower flammability (due to lower power density) compared to other chemistries but in the context of a fire of a battery pack it did not have a significant impact.

There are many parameters that influence the heat developed during a battery fire. The design of the battery pack enclosure and internal pack design are particularly important for reducing flame propagation.

6.2 Pressure build-up

The character of a thermal runaway involves a rapid increase in temperature and pressure due to gas formation and expansion. The pressure may build up within the cell but can also accumulate and build up the pressure within the battery casing. Prismatic and cylindrical cells are equipped with safety vents with controlled vent relief pressures, preventing premature and unwarranted venting, whereas pouch cells cannot withstand a high internal pressure without bursting open. In the case of an ignition of the volatile gases, this will result in a significant volume expansion. If this happens inside the cell there is a possibility that a cell case explosion can occur as a result of poor design or malfunctions. Another possible scenario is cell venting followed by accumulation of volatile gases within the battery that is ignited in a later stage. This causes a rapid volume expansion and the risk of explosion. The battery casings are therefore required to be designed with a vent or similar to permit venting and mitigate the risk of explosion.

DNV-GL examined fire behaviour of a large number of different cells, both prismatic and pouch, with a capacity range from 1.2 to 200 Ah [14]. They did not observe any battery exploding directly during the testing, but they did observe the energy of flammable flashovers. The power of these events varied significantly depending on the volumes of gases, duration of release, rates of ignition, etc. Observations of unconstrained pouch cells that burst open catastrophically under extreme heating conditions were also made. However, in a battery pack these cells would be compressed and as a consequence this does not represent a completely realistic scenario. However, it emphasises the importance of cells and batteries being able to vent and relieve pressure in a controlled way.

In the study for FPRF “Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results” full-scale heat release rate (HRR) and fire suppression testing was performed on large format electric vehicle battery packs. The focus was to assist emergency responders with questions regarding, personal protective equipment (PPE); firefighting suppression tactics; and the best practices for overhaul and post-fire clean-up [12]. No projectiles were observed from the battery packs in any of the tests performed. None of the batteries burst or exploded in any way; however, violent sparking was observed during an unsuppressed HRR test with free burn on one standalone battery [12]. No projectiles were observed in any of the full-scale testing of larger racks of batteries for energy storage systems performed for FPRF in another study [7].

It is commonly known that higher State of Charge (SOC) increases the likelihood for a violent thermal event in case of any abuse or other potential sources for failure. Several studies have also shown that the gas volume increases with increased SOC [[10] [16]]. If cells vent and gas accumulates inside a battery pack, the ignition would create a rapid expansion that could cause an explosion. However, no reporting of ‘explosions’ or projectile event was found in the assessed fire tests [14] [12] [7].

6.3 Toxic gases

The electrolyte in lithium-ion cells consists of volatile organic solvents and lithium salt, generally lithium hexafluorophosphate (LiPF6). The organic solvents are evaporated and released as flammable gas at increased temperatures. The volume and composition of the cell vent gas depends upon a number of factors such as cell composition, SOC and cause of venting [16] [7]. Vent gases may include volatile organic compounds (such as alkyl-carbonates, methane, ethylene and ethane), hydrogen, carbon monoxide, carbon dioxide, soot and other particulates containing nickel, cobalt, lithium, aluminium, copper [7] [13]. A major point of discussion is the amount of HF and other fluorinated compounds found in vent gases, because of their toxicity. HF is highly reactive and has etching qualities, causing severe burns. For entire battery packs, the contribution from other components such as plastic casing, etc. increases. Hydrogen chloride and hydrogen cyanide are toxic gases that have been found in battery fire gases [14]. Table 5 lists components that have been found in gas from cell venting, both with and without ignition (fire) as well as battery pack fires including casing and other components.

Gas analyses have been performed at varying system/component levels from fire tests of electrolyte to the fire testing of entire vehicles with battery pack. It has been questioned how results on cell level can be extrapolated to battery pack and realistic real-life conditions and there are still uncertainties in the amount of toxic gases that one could be exposed to in case of a battery fire.

In 2012, Lecocq et al. performed a study with fire tests of complete EV cars [17]. They found that both the normal ICE car and the EV car emitted HF in the smoke related to the coolant system. HF from the coolant system was generated early in the fire at high concentration levels whereas HF from the battery pack could be measured in a later stage and at lower concentration levels (around 100 ppm) but during a longer period of time. The total amount of HF was shown to be similar from the battery pack as from the coolant system.

In tests with a 100 kWh energy storage rack where cylindrical cells were forced into thermal runaway internally, a maximum level of 26 ppm HF was measured just at the exhaust vent of the cabinet. In this test the fire did not propagate within the entire pack but was limited to one module [7]. In this study, CO and CH4 were found in such quantities that the authors discussed the need for ventilation requirements if installed indoors. In an external fire test with the same system the maximum detection rate of 100 ppm HF was reached early in the fire and was ‘over range’ during the entire fire of about 3 hours, indicating HF levels were greater than 100 ppm.

Table 5: Gases found during measurement from cell venting or fire

Substance	Chemical safety [1]
H_2	Flammable
CO	Flammable, Acute toxic, Health hazard
CO_2	-
CH_4	Flammable
C_2H_4	Flammable, Irritant
C_2H_6	Flammable
HF	Corrosive, Acute toxic
POF_3	No information
HCl	Corrosive, Acute toxic
HCN	Flammable, Acute toxic, Environmental hazard
Li	Flammable, Corrosive
Co	Irritant, Health hazard
Ni	Irritant, Health hazard
Mn	Flammable
Cu	Acute toxic, Irritant, Environmental hazard
Al	Flammable

The National Institute for Occupational Safety and Health (NIOSH) provides exposure limits for toxic substances in work places. The Immediately Dangerous to Life or Health Concentrations (IDLH) for HF is 30 ppm (25 mg/m3) [18]. It has been stated that 50 ppm may be fatal when inhaled for 30 to 60 minutes [19]. Still there are limited experience of HF's impact on persons. Time weighted average (TWA) for 8 h day is 3 ppm [18].

Additional tests on pack level have shown various levels of HF. A study presented by Amstein Walthert showed levels of HF that were clearly lower compared to the other studies [13]. The same study measured high levels of Co, Li and Mn which may also constitute a chemical hazard.

The level of HF has also been measured for a broad range of commercial lithium-ion cells with different chemistry, cell design (pouch, cylindrical and prismatic) and size [16]. The amount of HF measured in the fire test ranged between 20 and 200 mg/Wh of nominal battery capacity. During this test, POF_3 was detected with just one out of the many cell chemistries and SOC tested [16]. No significant change in the constitution of gases emitted was observed when water was used as an extinguishing media. What could be seen was a higher concentration of HF produced during the

[1] Information regarding chemical safety is taken from the database PubChem from National Institutes of Health at NCBI homepage, U.S. National Library of Medicine [20].

actual spraying with water but the total amount of HF produced by the fire was still the same [21]. This study discussed whether more of the HF produced was bound to water droplets instead of being measurable as gas in the FTIR analysis when spraying with water.

Comparison of toxic gases (HCl, HF, HCN, CO, SO2 and H2S) from fires with plastic and batteries has also been performed [14]. The average emissions rate during a battery fire was lower per kg of material than for plastics fires. However, the peak emissions rate (during thermal runaway of a Li-ion battery) is higher per kilogram of battery than for plastics.

There are still open questions regarding the amount of HF that is produced during a battery fire. Questions have also been raised as to whether there are additional toxic substances in the smoke from a battery that differs from smoke from fires in general, and how much of these substances remain in the water after extinguishing a fire. Analyses have shown fluorides and chlorides in water samples collected after extinguishing lithium-ion battery fires [12].

6.4 Remarks regarding hazards specifically related to lithium-ion failures

The main hazards specifically related to lithium-ion battery failures could be linked to internal chemistry and the risk for thermal runway resulting in heat release, pressure build-up and toxic gases. There are many parameters that influence the severity of hazard developed during a battery fire:

- The design of the battery pack enclosure and internal pack design is particularly important for reducing flame propagation.
- It is commonly known that higher State of Charge (SOC) increases the likelihood of a violent thermal event in case of any abuse or other potential sources for failure. Several studies have also shown that the gas volume increases with increased SOC [[10] [16]].
- There are still open questions regarding the amount of HF that is produced during a battery fire. Questions have also been raised about the possibility of there being additional toxic substances in the smoke from a battery and whether these differ from smoke from fires in general.

7 Safety standards, codes, guidelines and regulations

During the last five years, as the battery energy storage industry has grown, several safety standards have been developed internationally for energy storage systems and large format lithium-ion batteries. It is organizations and companies such as International Electrotechnical Commission (IEC), Underwriters Laboratories (UL) in US, National Fire Protection Association (NFPA) in US and VDE Verband der Elektrotechnik Elektronik Informationstechnik e. V. (VDE) in Germany that have led the work to develop design, testing and installation requirements. The scope of the energy storage system standards includes both industrial large-scale energy storage systems as well as domestic energy storage systems. Appendix 1 includes a summary of applicable international standards for domestic battery energy storage systems (BESSs). When a standard exists as a British standard (BS) based on a European (EN or HD) standard, the BS version is referenced. The standards are divided into the following categories:

- Safety standards for electrical installations.
- Standards for grid connectivity requirements.
- Model codes for electrical installations on the US market.
- Safety standards for electrical energy storage systems.
- Safety standards for stationary lithium-ion batteries.
- Safety standards for lithium-ion cells.
- Functional safety standards for control and battery management systems.
- Lithium-ion battery transportation safety.
- Safety standards for power electronic converter systems and inverters.
- Standard for electromagnetic compatibility (EMC).

The need for clear standards and policies was a strong theme among the BESS stakeholders interviewed in this study. One concern is that standards tend to lag behind new innovations and that safety standards typically represent minimal requirements and are not aspirational. Interviews emphasized the role system installers play. Inherently safe BESSs may present hazards if electrical codes and BESS installation guides are not properly followed. System installers must therefore be well trained.

7.1 Safety standards and regulations in UK

The safety requirements in UK for BESSs can be divided into electrical installation requirements, grid connectivity requirements, product safety regulation requirements and dangerous goods regulation requirements.

7.1.1 Electrical installation and grid connectivity requirements in UK

All electrical installations with which the public come into contact as part of their normal day to day activities, must generally comply with the IET wiring regulation (BS 7671). Currently, there is no separate chapter for installations of electrical energy storage systems in BS 7671. Instead, requirements in applicable parts must be considered. BS 7671 does not incorporate specific requirements for domestic BESSs or their location in dwelling houses. A further guidance document, 'IET Code of Practice for Energy Storage Systems' was published in 2017 with a view to best practice for installations.

When connecting BESSs to the UK public Low Voltage Distribution Network, a specific procedure must be followed. The type testing and registration needed is described in G83/2 and G98/1. Engineering recommendation G98/1 is an update of G83/2. G98/1 came into effect on 17 May 2019 for micro-generators commissioned on or after that date.

7.1.2 Product safety and dangerous goods regulatory requirements

Each subsystem of the BESS should comply to applicable product safety directives such as:

- General product safety directive (as applicable).
- Low voltage directive (between 50 and 1000 V for AC, 75 and 1500 V for DC).
- EMC directive.

In addition, dangerous goods regulations require that lithium-ion batteries should be tested according to UN Manual of Tests and Criteria section 38.3 to be able to be transported.

7.1.3 Minimum requirements for domestic BESS in UK

All these requirements and the standards that are used to comply with them, are listed in Table 6. In a simplified view, the minimum safety requirements for a domestic BESS are dependent on whether the nominal voltage of the battery subsystem is lower or higher than 75 V. Most domestic battery energy storage manufacturers choose to have nominal voltages lower than 75 V. For battery subsystems with a nominal voltage higher than 75 V, the battery subsystem needs to comply with the low voltage directive as well.

Table 6: Minimum requirements for a domestic BESS in UK

Group	Standard	Comments
Electrical installation requirements	BS 7671	
Grid connectivity requirement	G98/1	
Product safety regulations: General product safety directive	BS EN 62619 (lithium-ion battery) BS EN 62619 (lithium-ion cells)	BS EN 62619 is not a harmonized standard with the general product safety directive.
Product safety regulations: Low voltage directive	BS EN 62109-1 and BS EN 62109-2 (inverter) or BS EN 62477-1 (inverter) BS EN 62477-1 (system*) or BS EN 62368-1 (lithium-ion battery and electrical subsystems)*	BS EN 62109-1, BS EN 62109-2, BS EN 62477-1 and BS 62368-1 are harmonized standards with the low voltage directive.
Product safety regulations: EMC directive	BS EN 61000-6-3 and BS EN 61000-6-1	BS EN 61000-6-3 and BS EN 61000-6-1 are harmonized standards with the EMC directive.
Dangerous goods regulations	UN 38.3	Lithium-ion batteries should be tested according to UN 38.3 in the same configuration as it is transported e.g. within a finished BESS, within a battery subsystem or as stand-alone modules.

*Only required if the nominal voltage of the battery subsystem is higher than 75 V

BS EN 62619 is listed in Table 6 as a minimum requirement. However, there are no specific references to BS EN 62619 in any regulation, since BS EN 62619 is not a harmonized standard to any directive. However, according to the general product safety directive, if there is an established applicable standard suitable for your product, this should be used to show the safety of your product. It is therefore recommended by several third-party certification organizations that a lithium-ion battery subsystem should comply to BS EN 62619. There is currently nothing in the regulations that stops manufacturers from using another lithium-ion safety standard such BS EN 62133-2.

7.1.4 Expected future minimum requirements for domestic BESS in UK

Several new standards for lithium-ion battery based electric energy storage systems are under development and have recently been published. In the near future, it is expected that the minimum requirements will be described by a longer list of standards that will make it clearer to the manufacturers which requirements they need to follow. It is expected that the list of standards will change to one listed in Table 7.

Table 7: Expected minimum requirements for a domestic BESS after new lithium-ion BESSs standards have been published

Group	Standard
Electrical installation requirements	BS 7671 IEC 62485-5* (lithium-ion battery specific installation requirements)
Grid connectivity requirement	G98/1
Product safety regulations: General product safety directive	Applicable parts of IEC 62933-5-2 (system) IEC 63056 (lithium-ion battery subsystem) BS EN 62619 (lithium-ion battery subsystem) BS EN 62619 (lithium-ion cells)
Product safety regulations: Low voltage directive	BS EN 62109-1 and BS EN 62109-2 (inverter) or BS EN 62477-1 (inverter) BS EN 62477-1 (system**) or/and BS EN 62368-1 (lithium-ion battery and electrical subsystems)**
Product safety regulations: EMC directive***	BS EN 61000-6-3 and BS EN 61000-6-1
Dangerous goods regulations	UN 38.3

* Standard currently under development
** Only required if the nominal voltage of the battery subsystem is higher than 75 V
*** The radio equipment directive is also applicable if the system includes a WiFi equipment

The major changes between Table 6 and Table 7 are:

- The manufacturer must take into consideration risks associated with combining battery subsystems and any electrical subsystems by applying IEC 62933-5-2. IEC 62933-5-2 includes clearer directions for how a risk analysis for the complete system should be conducted to consider these risks.
- IEC 62933-5-2 was published recently and includes references to specific component standards that should be applied, e.g. the current version includes a requirement that the

lithium-ion battery subsystem shall comply to BS EN 62619. Before, there were no specific references as to which lithium-ion battery safety standards should be applied in other standards or regulations.

- IEC 62485-5 will include specific installation requirements for lithium-ion battery systems that may be referenced in future versions of BS 7671. The current draft version requires that the lithium-ion battery system has been tested according to BS EN 62619. It will most likely be required in future versions of IEC 62933-5-2 that the installation shall comply to IEC 62485-5.

7.2 Remarks regarding development of standards for domestic BESS

At the present time there are no regulations or standards developed specifically for domestic BESSs for the UK market. The standards above have been developed for both large industrial BESSs and small domestic systems. For the US market, there is currently an effort to develop robust requirements for domestic energy storage systems (chapter 15 in the standard NFPA 855). For example, the current version of the chapter includes requirements for location in a dwelling house where a domestic BESS can be installed. It is expected that NFPA 855 may be referenced in future versions of the US codes (e.g. NFPA 70, the US version of BS 7671). There is ongoing discussion on which requirements should be included in the chapter.

Several standards that will be applicable for domestic lithium-ion battery storage are currently under development and not published yet. If these standards are developed with the objective of becoming harmonized standards under the Low Voltage Directive or General Product Safety Directive or referenced in other standards or regulations such as BS 7671 it would facilitate the clarity of the process for showing compliance with regulations.

8 Risk mitigation choices

Both the standard IEC 62933-5-2 and the US standard UL 9540 include requirements on reducing risk. The standards highlight risks that need to be reduced to acceptable levels. However, they do not specify how the manufacturer should reduce the risk.

The priority of risk mitigation methods that the manufacturer should use is:

- Inherently safe design.
- Guards and protective devices.
- Information for end users.

In the end, for both energy storage system standards and lithium-ion battery safety standards the manufacturer is required to show that their combination of design choices, guards and protective devices and documentation reduces the risk to tolerable levels in a risk analysis.

The manufacturer must consider all potential failures that may occur over the full life cycle of a domestic battery energy storage system (BESS) as part of the risk analysis. A failure induced in an earlier phase may result in a hazardous event in a later phase of the life cycle. Within the EU-project STABALID, a risk analysis was performed for stationary lithium-ion batteries [22]. This risk assessment was performed to support the deployment of safe lithium-ion stationary batteries with a cell size larger than 10 Ah and systems larger than 1 MWh. The study identified risks and hazards during the life cycle of the battery and presented a methodology for the risk assessment including risk mitigation measures. Even though the system sizes are larger than the domestic systems considered in this report, a similar approach could be taken when evaluating the risks for domestic battery energy storage. They include the following stages for the life cycle of the stationary lithium-ion battery:

- Production
- Transportation/removal
- Storage
- Installation/decommissioning
- Operation
- Maintenance/periodic inspection.

From a general perspective, recycling/destruction could be added as a separate stage at the end of the lifetime.

8.1 Causes for failure

In this report no specific risk assessment is presented for each phase of the life cycle. Instead, failure causes for the two main hazard groups, thermal runaway and electrical hazards, are presented in general categories based on their character.

8.1.1 Causes for thermal runaway

The central event for lithium-ion battery hazards is the thermal runaway that constitutes a hazard in terms of increased temperature/fire, increased pressure and release of toxic gasses. On a system level, it is the risk for cascade propagation of thermal runaway in one cell spreading to other cells resulting in thermal runaway within the entire pack that is the central hazardous event. Assessment of the propagation of a cell failure is captured in the standards applicable for domestic lithium-ion battery storage systems such as BS EN 62619, UL 1973, UL 9540 and IEC 62933-5-2.

The failure causes of thermal runaway could be divided into the general categories of mechanical, electrical and environmental abuse as well as faults induced into the system at the production stage. Examples of failure causes are described separately in each section below from a general perspective.

8.1.1.1 Mechanical

Examples of mechanical abuse may include the following: vibration, crush, drop or puncturing and could for example lead to rupture of cell casing or cell internal short circuit which may lead to a thermal runaway.

8.1.1.2 Electrical

The cell needs to be kept within its voltage and current limits for a safe operation. Exposure to electrical abuse such as external short circuit, overcharge or over discharge may lead to thermal runaway.

8.1.1.3 Environmental

As described previously in section 6, it is important to keep the cell within the operating temperature range. It is one of the most important environmental parameters to consider in the risk analysis. External heating or fire could damage the cell and start reactions within the cell that could lead to swelling, gassing, venting and in worst case a thermal runaway. Charging at low temperatures can lead to lithium plating and cell internal short circuits that could also result in thermal runaway.

8.1.1.4 Manufacturing and design issues

The risk for internal short circuit due to manufacturing faults is difficult to capture in a standardised safety test. The cell manufacturing quality and controls are therefore of great importance in order to avoid cell internal short circuits from the manufacturing process. Safety standards for lithium-ion cells and batteries generally have a requirement for a certain level of manufacturing process control. The IEEE 1725 standard for rechargeable batteries for cellular telephones has the most detailed requirements regarding manufacturing control [23]. An audit protocol for evaluation against IEEE 1725 has been developed by CTIA – the wireless association, identifying critical manufacturing processes such as: electrode coating, burrs, impurities, misalignment of electrode/separator, etc.

Since there are several layers of safety functions in place on a cell, battery and system level, it can often be a combination of abuse condition and faulty design or manufacturing defect that causes the thermal runaway.

8.1.2 Causes for electrical hazards

Electrical hazards are present on the system level in the battery subsystem when the cells are connected to give higher voltage and in the power conversion subsystem. The electrical hazards could be electrical shock or arc flash if the voltages are at such high levels. There may be various types of abuse that result in electrical shock but a basic criterion is access to conducting parts. The root cause could be mechanical damage to casing or short circuit of loose cables, etc. Environmental conditions such as moisture or rain could cause corrosion and short circuits within the system. An arc flash happens when there are two conducting parts with high voltage in the vicinity of each other with insufficient isolation. The arc flash could result in a thermal event with fire, depending on the surrounding materials.

The impact of failure within the Power Conversion Equipment (PCE) or excess current drawn by the AC load is discussed briefly under section 8.3 of this report.

8.2 Battery subsystem

8.2.1 Cells

In a lithium-ion battery safety standard such as BS EN 62619, it is required that the cells should not present significant hazard under conditions of both intended use and reasonably foreseeable misuse. That means that the cell should not explode or produce fire during:

- An external short circuit (≈30 mΩ).
- An impact condition (impact from a 9.1 kg rigid mass).
- A drop (often from a height of 1 m).
- An exposure to high temperatures (85 ˚C for 3 hours).
- A foreseeable overcharge condition.
- A forced discharge condition (a discharged cell is discharged for a further 90 minutes).

It is also desirable (even though not explicitly required in BS EN 62619) that cell design should be able to minimize the effect of an internal short circuit or reduce the risk of an internal short circuit.

Cell manufacturers achieve their specific performance and safety characteristics through a careful optimization and combination of the material properties of their chosen anode material, electrolyte, separator and cathode material and design choices. Below are some examples of safety related material and design choices such as (but not limited to):

- The use of electrolyte additives
  - preventing side reactions that could cause heating, gassing and inhomogeneities,
  - flame retardant reducing the risk for fire in case of venting or a thermal event,
  - over charge redox shuttles and other additives reducing the risk at over charge, etc.
- The use of specially designed separators e.g.
  - ceramic coated separators in order to add mechanical strength, reduce shrinkage, and increase high-temperature performance,
  - separators with shutdown functions that cause the melting of the separator in case of a small local internal short that isolates the short circuit.
- Safety functions built in the cap/casing of cylindrical/prismatic cells.

- PTCs (Positive Thermal Coefficient) that increase the resistance at high temperatures in case of an overcurrent,
- CIDs (Current Interrupt Devices) that electrically disconnects the cell at high internal cell pressure,
- safety vents in the cell enclosure (requirement in most safety standards for lithium-ion cells) that release the pressure at high internal pressure to avoid explosion of the can/casing.

Cell manufacturers can also reduce the risk of a hazardous event caused by an internal short circuit, by having process controls in place that continuously monitor key elements of the manufacturing process which could affect safety. This is not explicitly required in safety standards for lithium-ion cells such as BS EN 62619.

8.2.2 Battery management systems

Even if lithium-ion cells are not exploding or producing fire during foreseeable misuse, when tested separately, this does not mean that they will not present any significant hazard when they are connected to each other to form a battery. It is required in lithium-ion battery standards such as BS EN 62619 that the battery manufacturer shall design the battery system to comply with the cell operating region. A battery manufacturer achieves this through a battery management system (BMS) that monitors and controls each cell voltage, discharge current and charging current. The BMS should also monitor the interior battery temperature and prevent charging outside the cell's recommended temperature range for charging.

In summary, a BMS should:

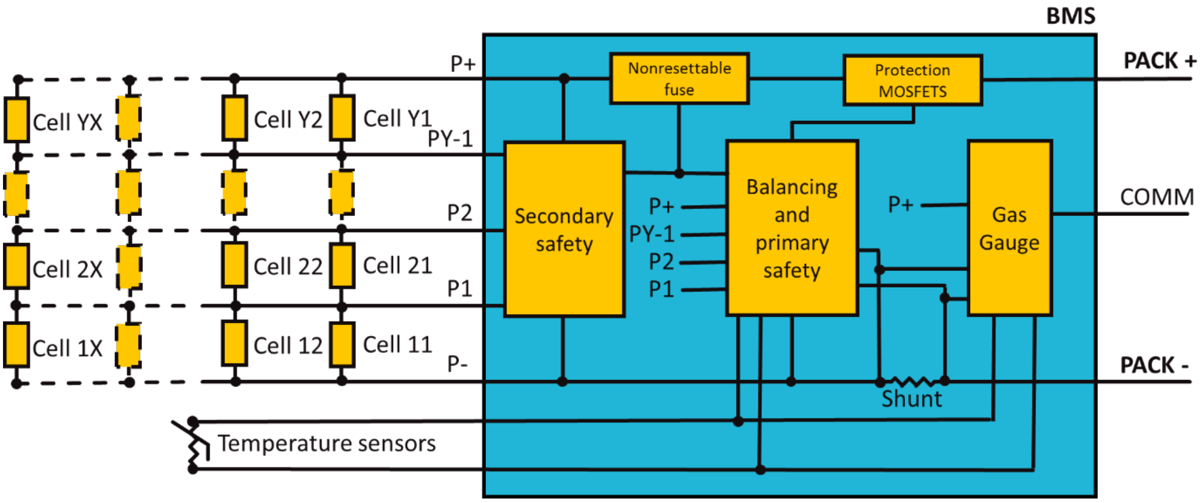
- Control cell voltages to prevent over charge and over discharge conditions.
- Control the charging and discharging current to prevent overcurrent and short circuit conditions.
- Control the temperature to prevent overheating conditions.

It is often required in safety standards for stationary lithium-ion batteries, that the BMS should be able to ensure protection under a single component failure or software failure in the BMS. Battery manufacturers can achieve this through a combination of design choices such as:

- Using multiple independent levels of protection for the control of temperature, current and cell voltage.
- Ensure compliance to functional safety standards for safety critical components (software and hardware).
- Using fail safe components.

An example of a typical BMS is shown in Figure 4. In this design, the voltages of each cell unit (group of parallel connected cells) are monitored by two independent components (primary and secondary safety). The two components can switch off the discharge or charge current, blowing a non-resettable fuse or activate the protection MOSFETS. The temperature and current (measured through the shunt) are also monitored and the safety components can switch off the current in case the temperature or current is outside the cell's recommended current and temperature range.

Figure 4: Schematic of a typical BMS



If a BESS is divided into several packs or modules, a BMS similar to the design in Figure 5 is often found in each pack or module. Each BMS communicates alarms and status of each module or pack to a battery management unit or control subsystem (see Figure 1).

8.2.3 Physical design of battery subsystem

Many lithium-ion battery standards such as BS EN 62619, UL 1973 and IEC 62933-5-2 require that a single cell failure should not propagate outside the enclosure of the battery subsystem. In addition, a design of a battery subsystem should allow for swelling (if pouch cells are used) and minimize the temperature rise inside the modules during normal operation.

Battery manufacturers achieve this through a combination of design choices such as (but not limited to):

- Adding physical spacing between cells/modules to allow for swelling and reduce the risk for propagation of heat and/or flames.
- Adding heat sinks and thermal barriers.
- Using a thermal management system with active liquid or air cooling.
- Considering the location of cell vents to minimize the risk for affecting other cells or lost functionality of BMS or safety circuits.
- Reinforcing the cell casing to fail safe and prevent rupture of the cell during cell failure.
- Minimizing the availability of oxygen inside the battery module.
- Using individual cell fuses to prevent discharging of parallel connected cells through a failed cell.
- Optimizing the placement and number of temperature sensors.
- Optimizing the total energies of the battery modules with regards to safety.

To ensure an inherently safe design of a battery energy storage system (BESS) in terms of fire propagation, draft standard IEC 62933-5-2 requires that the inside of the BESS shall be separated into battery section, charging equipment section and section including circuit breaker and discharge circuit, using fire-proof partitions.

8.2.4 Enclosure design

A battery subsystem needs to be protected by an enclosure. A battery manufacturer should consider whether an enclosure design has some or all of the following properties:

- Ability to resist possible physical abuse during reasonably foreseeable misuse.
- Capable of resisting ingress of moisture (depending on the location of the installation).
- Provides protection from internal projectile of cells.
- Prevents access to hazardous parts.
- Limits spreading of fire.
- Avoids pressure build up and explosion.
- Has a sufficient flammability rating if using polymer materials.
- Is resistant to corrosion if using metallic enclosures.

Standards such as the EN 60529 series are used to define Ingress Protection (IP) requirements. Most enclosures on the market in systems today are not rated for external mounting (with the exception of the Tesla Powerwall which has active temperature control and achieves an IP56 rating).

BS EN 62619 and other battery standards require also that:

- Wiring and its insulation shall be sufficient to withstand the maximum anticipated voltage, current, temperature, altitude and humidity requirements.
- The design of wiring shall be such that adequate clearances and creepage distances are maintained between conductors.
- Hazardous live parts of the battery system shall be protected to avoid the risk of electric shocks.
- The mechanical integrity of the connections shall be sufficient to accommodate conditions of reasonably foreseeable misuse.

8.3 The power conversion subsystem (charger/inverter)

The charger/inverter provides the point of connection to the public supply and therefore provides both critical safety and performance functions.

Safety functions provided include:

- Overvoltage, surge protection on AC supply.
- Current monitoring and overcurrent protection.
- Short circuit protection.

- Thermal protection (on power devices and as a consequence of fan failure etc).
- Anti-island.

An ‘Anti-islanding’ function ensures that in the event of the loss of grid supply, the Energy Storage System does not attempt to feed power back onto the network. This has both a vital power quality and safety implication which are addressed by isolating and switching the system off.

Performance functions provided include:

- Grid under or overvoltage detection and protection.
- Grid under or over frequency detection.
- Loss of mains/anti-island.
- EMC filtering (may be external to the inverter).

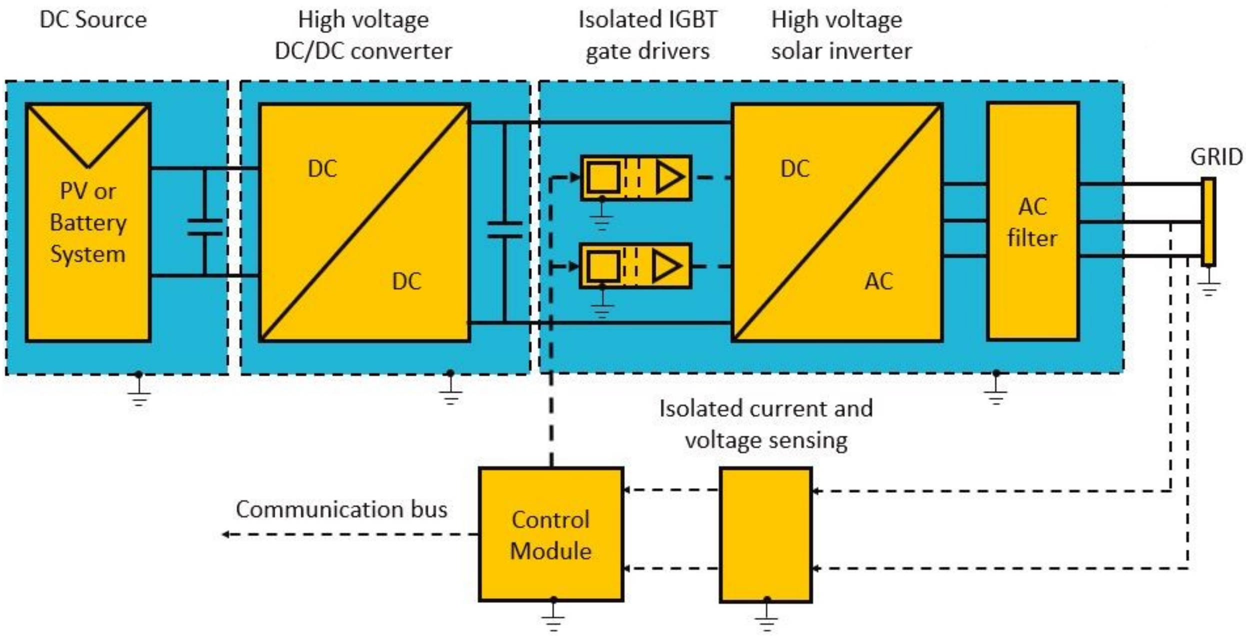
These performance functions are provided to ensure the power quality is maintained and that the local energy storage/generation system cannot operate in an ‘islanded’ mode if the utility grid supply is lost. This anti-island function is both a performance (power quality) and a vital safety function since it ensures that the source of distributed power is safely disconnected from the grid.

The safety standards covered in section 7 apply to the charger/inverter. In general, inverters used in these simple DC to AC (e.g. PV) applications are ‘transformerless’ meaning that there is no physical separation between the DC-DC side and the AC inverter side of the unit. Instead, safety isolation is provided by isolating the controls to the AC inverter (e.g. the gate signals for IGBT type devices) and the voltage and current sensors. Communications to the controller (e.g. via CAN or Ethernet) may also be fully isolated but are omitted from the block diagram below for clarity (see Figure 5).

Inverters/chargers used in BESS may operate in a full bridge mode with transformer isolation allowing bi-directional transfer and conversion from battery to grid and grid to battery.

The majority of BESS products are intended to be used in a grid connected application and therefore provide an AC supply output. Some commercial BESS (e.g. Moixa) can alternatively deliver a low voltage DC supply which provides a local DC supply for lighting purposes.

Figure 5: Block diagram of a typical power conversion subsystem



For BESS systems supplied as 'storage only', the choice of inverter is the responsibility of the system designer. Installation is more complicated than with a single box integrated BESS solution as the cabling and protection for the DC side between the batteries and the inverter is external to both products. Inverters used for these applications may be offered with 5-10 years warranties.

This report does not discuss failure mechanisms within inverters in depth. However, given that the battery cells represent a low impedance source, the potential for high current flow and fire risk exists.

The primary mechanism for limiting current at the Power Conversion Subsystems (PCS) input is provided by the BMS through monitoring of charge and discharge current and overcurrent due to potential short circuit. Many PCS utilise inverters designed in accordance with standards such as IEC/EN 62109 Part 1 and Part 2. These standards require testing to verify safe operation under a single fault or abnormal condition as dictated by Clause 4.4. 'Testing in single fault condition'. This defines detailed requirements for the single fault conditions to be applied with Clause 4.4.4.1 detailing 'Component fault tests' – this is performed by circuit analysis and determining the effect of open and short circuit of relevant components.

Clause 9 covers 'Protection against fire hazards' and specifies requirements intended to reduce the risk of ignition and flame propagation. This includes requirements for 'Resistance to fire', 'Limited power sources' and 'Short-circuit and overload protection'.

A useful reference published by the IEEE 'The Effect of Inverter Failures on the Return on Investment of Solar Photovoltaic Systems' [24] provides a useful field based review of typical inverter/PCS failures. The report notes that the main sources of failure (other than No-fault found) are:

- AC Contactor (12%)
- Fans (6%)
- IGBT or similar (6%)

- PSU (5%)
- AC Fuses (4%)

DC Input fuses comprise 2% of failure.

8.4 Control subsystem

The controller is responsible for the overall operation of the BESS in response to inputs from a variety of different sources:

- Direct monitoring of AC current flowing from or to the grid (via the final meter).
- Monitoring of AC voltage and frequency for both control and protection functions.
- Monitoring of DC current/voltage or state of charge of batteries.
- Health status (e.g. temperature alarms, etc).
- Profile or controller strategy (e.g. storage of excess energy generated by PV system, peak load shifting by buying low cost energy off-peak and using stored energy at peak times, grid balancing and trading (tariff arbitrage) or back up power systems).
- Communications via CAN or Ethernet (and subsequently wireless) – largely monitoring.
- Setpoint control for the inverter/charger (including Maximum Power Point Tracking (MPPT) for systems utilising solar PV).

Some of the protection monitoring functions (particularly those associated with the grid interface) may be provided by the charger/inverter.

The controller forms the heart of the BESS and in many cases will be the manufacturers' primary intellectual property.

This controller is often also described as the BMS (a separate function to any that might be embedded within the batteries themselves). The controller performs overall battery monitoring, operational control according to stimuli as described above, energy balance management (to/from grid and to home load), protection and alarms and communications. The controller will optimize state of charge of the batteries to maximize battery life or availability depending on the selected strategy and mode of operation. As an example, a system optimised for self-consumption might permit state of charge down to 30% whereby 30% of stored energy is retained for potential export to the grid compared with a system that only permits state of charge to say 70% and which is therefore optimised for grid availability.

Current monitoring is provided by means of current clamps. A single clamp for current to and from the grid is supplied with all systems. Systems that integrate with a pre-installed PV system or that integrate the PV panel DC source may be provided with additional current clamps to monitor the PV supply.

8.4.1 External interface and communications

Data communication is a key part of the BESS. Access for installers and configuration, remote monitoring and duty by the OEM and remote tracking by the end user via a mobile device or other client is provided.

Backbone communications may be via cabled Ethernet with a connection back to the home router to provide internet access or wireless communications may be provided by an external access point or internally via a dedicated Wi-Fi module. The latter introduces a level of compliance complexity since the complete BESS then becomes a ‘Radio Device’ and Safety, Spectrum and EMC will all be assessed under the EU Radio Equipment Directive (RED).

Given that many ES technologies have been developed for the Automotive market Controller Area Network (CANBus) may be utilised for internal communications and co-ordination. This interface is also commonly employed in industrial scale BESS systems but is less likely to be used as an external interface for domestic systems.

Cellular communications modules (2G/3G) are included in some BESS.

8.4.2 Display and HMI

In general, BESS products surveyed from the market are essentially ‘blind’ products. Products may be installed in a variety of locations including exterior or garage locations so the need for local display or operation is minimized.

All products include a communications interface which may be wired or incorporate a local wireless access point. Access for product configuration and application selection (for the system integrator) may be via a web-based application or mobile application hosted on an IOS or Android based device. Remote monitoring of the installed base including usage patterns is provided by the manufacturers post installation. Whilst outside the scope of this report, significant amounts of user data and behaviour patterns are exchanged and consideration of cyber-security and vulnerability must be a major focus.

For the end user, the ability to monitor return on investment and energy flows e.g. between Grid to/from storage, solar (if included) to grid/home/storage and to home (load) are also monitored via the communications interface.

Some products (e.g. the Duracell Energy Bank 3kW) include panel mounted switches for local/remote selection and power. Most products incorporate some form of simple status indication covering communications activity etc.

8.5 Auxiliary subsystem

8.5.1 Ventilation and cooling

Installation of the BESS in line with manufacturers recommendations is important to ensure reliable operation. This will include guidance on siting and location (e.g. Interior/exterior, wall or floor mount and environmental conditions) and clearance required around the unit to ensure adequate ventilation. All units surveyed include some form of open ventilation within the enclosure.

Cooling may be provided by fan assisted air cooling with the construction and layout optimised to natural chimney effects and ensure best flow of air over the battery and the charger/inverter. Some manufacturers interviewed have conducted heat surveys and carried out modelling of heat flow within their products.

Larger domestic BESS systems including the Tesla Powerwall employ an internal liquid cooling system and heat exchange mechanism.

Maintenance considerations including cleaning of vents/fans or checking of sealed systems must be documented as part of the manufacturers installation and operation manual.

8.6 The installation of a battery energy storage system

BESS manufacturers can also reduce the risk of a possible hazardous event by allowing only qualified installers and making recommendations regarding:

- Location of installation.
- Recommendations of separation between units and between the system to combustible materials.
- Fire detection requirements/fire suppression requirements.
- Ventilation requirements.

Representatives from the London Fire Brigade also expressed their desire to see a registry of BESS installations, a standardization of BESS location within a residence, and a readily available and visible BESS shutdown switch.

8.6.1 Protection

A BESS for UK application must be installed in accordance with the UK Wiring Regulations (BS7671:2018 or the IET Wiring Regulations). Whilst the regulations were updated in 2017 they do not include a BESS installation specific chapter.

In the absence of BESS specific coverage, section 712 of BS7671:2018 covers PV installations and is a useful reference. Furthermore, the IET Code of Practice for Energy Storage Systems provides more specific information.

Protection within the context of an integrated BESS comprises internal protection functions e.g. grid protection and isolation and external protection – e.g. installation components.

In cases where a separate battery and power conversion system is installed, or where PV is to be integrated with the BESS, all protective and switching devices for DC use must be rated appropriately and be capable of handling bi-directional current (during both charge and discharge).

The system controller described in section 8.4 provides battery monitoring and management at a battery bus bar level. Whilst individual battery modules will incorporate a Battery Management System (BMS) at a cell/pack level, a complete energy storage system will comprise several battery modules or may be expandable, allowing additional batteries to be added as load demand increases.

For BESS that comprise multiple battery modules, the means of connection (hard wired bus-bar or cabled distribution) and the means of interconnection (plug and socket, pre-coded cables or terminal blocks) requires careful consideration. In all cases, the installation instructions must provide clear instruction on how to fit and interconnect batteries.

A double pole battery isolator may be incorporated as part of the BESS control panel or internal to the unit. This would normally be located both physically and electrically close to the battery (or batteries) and isolate the DC supply to the inverter input. For systems with a DC bus bar voltage of 48V or less, the isolator may be omitted but is essential for any system operating above 120V DC (as per the IET Wiring regulations).

Battery protection in the form of a DC fuse (or other suitable protective device such as an MCB or MCCB) should be provided in addition to any electronic overcurrent protection offered by the charger/inverter.

Domestic BESS may be used as standalone systems or be used in conjunction with a Solar Photovoltaic (PV) panel installation. The provision of the PV system requires additional considerations for the installation.

- For a previously installed PV system with a separate solar PV inverter, all of the required DC isolation and AC isolation and connection to grid (behind the meter) will already be in place.
- For a BESS that is to be supplemented by a dedicated PV system, the BESS may act as the common point of connection and therefore may incorporate additional DC isolation for the PV modules (since the PV system cannot be switched off) and routing to enable battery charging or solar PV generation to be manged by the common inverter.

The DC isolation for the PV array may be separate or included as part of the inverter. Separate isolation is advisable as it makes the function clearly visible.

Cable identification and colour coding should follow the recommendations of the IET Wiring Regulations (BS 7671) which in turn references EN 60445:2017 'Basic and safety principles for man-machine interface, marking and identification. Identification of equipment terminals, conductor terminations and conductors'. The colour coding for DC cabling (Brown is Positive, Grey is Negative) is often supplemented with alphanumeric marking to avoid confusion with AC wiring.

AC wiring should be installed in accordance with the BS7671:2018 standard and following cable sizing and type requirements. A dedicated AC isolator must be installed in order to isolate both the AC supply to the BESS and the AC output from the inverter. This isolator can be a single unit.

The AC supply connection is made to a dedicated MCB or RCBO on the consumer unit. All protection and isolation components must meet the relevant electrical equipment standards listed in BS7671:2018 and will be listed on the Electrical Installation Certificate (EIC).

It should be noted that the latest edition of the BS7671:2018 recommends the use of Surge Protective Devices (SPD) for Domestic installations. Section 534 of the standard covers this requirement.

8.6.2 Generation meter

Systems that incorporate PV modules may also include a separate generation/export meter. In the case of systems designed for 'self-consumption' (with or without PV) an export meter will not be required.

8.7 Best practice and guidelines for energy storage systems and installations

As shown in section 7, there are a number of available standards and standards under development that address the safety of battery energy storage and their installation. This section has described some of the risk mitigation choices for the system mainly based on standards. The standards do cover a major part of the risks concerned but still there may be some areas that are missed out. In recent years, some countries have developed guidelines in order to assist suppliers, installers and others with guidelines on how to fully cover the safety of the systems and their installation. Below are three examples of guidelines developed with the intention to include different aspects and risks regarding battery energy storage and how to show compliance.

- UK: Code of Practice for Electrical Energy Storage Systems, IET standards [25].
- Australia: Best Practice Guide: Battery Storage Equipment - Electrical Safety Requirements [26].
- Germany: Safety Guideline Li-ion Home Storage Systems [27].

9 Concluding remarks

The domestic battery energy storage market is dominated by lithium-ion battery technology, but the market is still quite small compared to other lithium-ion battery applications. Currently, there have been few incidents of domestic BESSs known in the public domain but, due to the large energy content of the devices, there has been an effort to create new studies and standards.

Experience with fires involving domestic lithium-ion battery storage systems is limited. The worldwide growth of EV and BESS applications demand an improved understanding of how large battery systems behave when abused. Based on a small number of recent studies, the major lithium-ion battery fire characteristics can be summarized in the three hazard categories listed below:

- 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 is key to avoiding thermal runaway of the full system.
- Cell and pack failures can generate large volumes of gasses resulting from the rapid pressure build up and vent release as the system heats up. Management of gasses generated must be considered in pack and system design.
- The toxicity of gasses generated from battery fires may require specific consideration to ventilation systems.

There are many possibilities for risk mitigation on all levels from the cell to the system design and installation of the system. Many of the risks and requirements for mitigation are captured in the existing standards or standards under development. Below are some considerations regarding risk mitigation:

- The 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 5kWh BESS containing 500 18650 cells). This is not to say that 1 in 10,000 BESS will fail catastrophically. 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.

Several standards that will be applicable for domestic lithium-ion battery storage are currently under development or have recently been published. The first edition of IEC 62933-5-2, which has recently been published, covers the safety of domestic energy storage systems. It will most likely be required in future versions of IEC 62933-5-2 that lithium-ion battery subsystems shall comply with BS EN 62619, IEC 62485-5 (under development) and IEC 63056. If these standards are developed with the intention of being harmonized standards under the low voltage directive or general product safety directive or referenced in other standards or regulations such as BS 7671, it would facilitate the clarity of the process for showing compliance with regulations. Current battery subsystems are often only tested to BS EN 62619.

10 References

[1] M. Jacoby, "Safer Lithium-ion Batteries," *Chem. & Eng. News,* vol. 91, pp. 33-37, 2013.

[2] "Solar Guide - Solar Battery Storage: The Best Solar Batteries," [Online]. Available: https://www.solarguide.co.uk/solar-batteries#/. [Accessed 6 August 2019].

[3] L. A. McKenna, "Electronic Cigarette Fires and Explosions in the United States 2009 - 2016," Research Group National Fire Data Center, U.S. Fire Administration (USFA) FEMA, 2017.

[4] FAA, "Aviation Cargo and Passenger Baggage Events Involving Smoke, Fire, Extreme Heat or Explosion Involving Lithium Batteries or Unknown Battery Types," 2019.

[5] BRE National Solar Centre, "Fire and solar PV Systems - Investigations and evidence report," BEIS, 17 July, 2017.

[6] A. Chiaramonte, A. Smith and Z. Hood, "Fire Safety of Solar Photovoltaic Systems in Australia," Worcester Polytechnic Institute (WPI) and Alternative Technology Association (ATA), May 2016.

[7] A. f. Blum and T. R. Long, "Hazard Assessment of Lithium Ion Battery Energy Storage Systems," Fire Protection Research Foundation, Massachusetts, 2016.

[8] TUV Rheinland, "Anlagenabnahme im SPEISI Projekt," Feuerwehr workshop SPEISI, 31.01.2017.

[9] "IEC 62660-2 Secondary lithium-ion cells for the propulsion of electric road vehicles- Part 2:Reliability and abuse testing".

[10] C. Chanson and P. Bermis, "Li-batteries hazard classification" Recharge, UN Informal Working Group meeting "Hazard based classification of lithium batteries"," Geneva, December 6-8 2017.

[11] T. R. Long, J. A. Sutula and M. J. Kahn, "Lithium-Ion Batteries Hazard Phase IIB," Fire Protection Research Foundation, Quincy, MA, 2013.

[12] R. Long, A. Blum, T. Bress and B. Cotts, "Emergency response to incidents involving electric vehicle battery hazards," Fire Protection Research Foundation, July 2013.

[13] U. Welte, "Electric Mobility: New Risks In Underground Facilities", Amstein-Walthert Swiss research project, ITA COSUF Workshop On New Energy Carriers In Road Tunnels," Utrecht Netherlands, February 15 2019.

[14] Hill, Davion, DNV-GL, "Considerations for ESS Fire Safety, Consolidated Edison and NYSERDA," DNV-GL, 2017.

[15] J. Harmon, P. Gopalakrishnan and C. Mikolajczak, "US FAA-style flammability assessment of lithium-ion batteries packed with and contained in equipment (UN3481)," US Government Docket ID: PHMSA-2009-00095-0117, 2010.

[16] F. Larsson, P. Andersson, B. Per and B.-E. Mellander, “Toxic flouride gas emissions from lithium ion fires,” vol. 7, 2017.

[17] A. Lecocq, M. Bertana, B. Truchot and G. Marlair, “Comparison of the fire consequences of an electric vehicle and an internal combustion engine vehicle,” International Conference on Fires In Vehicles - FIVE 2012, Sep 2012, Chicago, United States, 2012.

[18] “CDC - NIOSH Pocket Guide to Chemical Hazards,” [Online]. Available: https://www.cdc.gov/niosh/npg/npgd0334.html. [Accessed 15 04 2019].

[19] G. H. Deichmann WB, “Hydrofluoric acid (hydrogen fluoride, HF). In: Toxicology of drugs and chemicals.,” Vols. pp. 317-318., 1969.

[20] NCBI, “PubChem,” [Online]. Available: https://pubchem.ncbi.nlm.nih.gov/. [Accessed 14 April 2019].

[21] P. Andersson, P. Blomqvist, . A. Lorén and F. Larsson, “Investigation of fire emissions from Lithium ion batteries,” SP 2013-15, Borås , 2013.

[22] F. Soares, L. Carvalho, I. Costa, J. Iria, J.-M. Bodet, G. Jacinto, A. Lecocq, J. Roessner, B. Caillard and O. Salvi, “The STABALID project: Risk analysis of stationary Li-ion batteries for power system applications,” *Reliability Engineering and System Safety,* vol. 140, 2015.

[23] “IEEE 1725 Standard for Rechargeable Batteries for Cellular Telephones”.

[24] T. J. Formica, H. A. Khan and M. G. Pecht, “The Effect of Inverter Failures on the Return on Investment of Solar Photovoltaic Systems,” vol. 5, pp. 21336-21343, 2017.

[25] IET, Code of Practice for Electrical Energy Storage Systems, 2017.

[26] Battery Safety Guide, “Best Practice Guide: Battery Storage Equipment – Electrical Safety Requirements.,” 6 July 2018. [Online]. Available: http://www.batterysafetyguide.com.au/.

[27] VDE, VDE-AR-E 2510-50 Stationary battery energy storage systems with lithium batteries - Safety requirements, 2017.

Appendix 1: General hazards with domestic battery energy storage systems

According to NFPA 855 and IEC62933-5-2 (see Appendix 2 for a description of standards), the hazards for a domestic battery energy storage system (BESS) could be summarized in following categories: fire and explosion hazards, chemical hazards, electrical hazards, stranded or stored energy and physical hazards. The hazards for a battery pack on system level originates from the cells and the hazards on a single cell level. When the cells are electrically connected and placed together this could both introduce new hazards as well as increase or decrease the hazards from a single cell perspective.

Hazards are typically divided into normal operating conditions and abnormal/abuse conditions where the latter considers all abuse to be external to the battery and cell whereas under normal operation there is no external abuse. Table A 1 displays the overall hazards for domestic energy storage systems with lithium-ion batteries.

Table A 1: Hazards for lithium-ion BESSs according to NFPA 855

Hazard	Normal operating condition	Emergency/Abnormal operating conditions
Fire and explosion	There may be a potential for thermal runaway resulting in fire or explosion if there are latent faults induced during manufacturing of the cell.	There may be a potential for thermal runaway if the batteries are not maintained at appropriate operating parameters as a result of abnormal conditions. Also, there might be fire hazards due to short-circuiting under abnormal conditions.
Chemical	Lithium-ion batteries are sealed batteries but there may be a potential for thermal runaway resulting in fire or venting with toxic fumes if there are latent faults induced during manufacturing of the cell.	There may be a potential for thermal runaway releasing hazardous smoke and venting of hazardous vapours if the batteries are not maintained at appropriate operating parameters.
Electrical	There are electrical hazards associated with routine maintenance if they are at hazardous voltage and energy levels.	Electrical hazards might be present under abnormal conditions if the system is at hazardous voltage and energy levels.
Stranded energy	There can be the potential for stranded or stored energy hazards during maintenance if the batteries cannot be isolated for maintenance or replacement.	There can be the potential for stranded or stored energy hazards during maintenance if the batteries cannot be isolated for maintenance or replacement.
Physical	None.	Depending on the design of the system, the potential exists for physical hazards under abnormal conditions if accessible parts are overheating.

The fire and explosion hazards are described in section 6, where a thermal runaway event for lithium-ion batteries is described. Specifically, section 6.1 and 6.2 describe the heat and gas release during a thermal event that can occur during emergency/abnormal conditions. If concentrations of vented flammable gases are sufficient to create combustible/flammable concentrations in the presence of hot parts, there will be ignition resulting in either a fire or an explosion. However, the ignition heat could also come from the cell interior. All lithium-ion batteries, with a very few exceptions, have means to relieve internal pressure when overheated to prevent explosions of the battery cell from over pressurization. However, sometimes the thermal runaway reaction could result in such a rapid increase in pressure inside the cell that it causes explosion.

There can also be fires due to overheating of electrical parts under abnormal conditions such as short circuits.

The chemical hazard of the system is related to the vent and fire gasses coming from the lithium-ion cell. The toxicity of the gases is described in section 6.3.

The electrical hazard is related to the risk of electrical shock due to the system voltage. Circuits with voltages above 50 V have the potential for electrical shock hazards. In the case of high voltage systems there is also the hazard of arc flash and arc blast. The risk is especially high for first responders and maintenance staff.

Stranded or stored energy hazards is where the hazard related to energy stored within the system cannot be discharged after an emergency incident for maintenance or replacement. It therefore presents potential shock, arc flash, arc blast, and re-ignition hazards.

The physical hazard depends on the design of the system, for example if accessible parts are overheating or if there is exposure to moving hazardous parts such as fans where guards might be missing.

Appendix 2: International safety standards and codes

Safety standards for electrical installations

A domestic battery energy storage system (BESS) will be part of the electrical installation in residential buildings. Examples of standards that cover electrical installations in residential buildings are shown in Table A 2. The HD 60364 series is a harmonization document from CENELEC. The series is used as a basis for the national standards for each European country.

In the UK, it is the IET wiring regulations (BS 7671) that provide the national standard for electrical installations. Both BS 7671 and the HD 60364 series give the rules for the design, construction, and verification of electrical installations. The rules are intended to provide for the safety of persons, livestock and property against dangers and damage which may arise in the reasonable use of electrical installations and to provide for the proper functioning of those installations. All electrical installations with which the public come into contact, as part of their normal day to day activities, are generally within the scope of and covered by BS 7671 and the HD 60364 series. Currently, the IET wiring regulation does not include a separate chapter for electric energy storage systems like BESSs. Instead, applicable parts need to be found by the installer.

Table A 2: Example of international safety standards and codes for electrical installations.

Standard #	Name	Pub. year	Valid in Country
BS 7671	Requirements for Electrical Installations. IET Wiring Regulations	2018	UK
HD 60364 series	Electrical Installations for Buildings	2005-2018	Harmonization document from CENELEC. Used as a basis for national standards in European countries.

Table A 3: Standard for prosumer's low-voltage electrical installations

Standard #	Name	Pub. year	Scope

HD 60364-8-2	Low-voltage electrical installations - Part 8-2: Prosumer's low-voltage electrical installations	2018	This part of HD 60364 provides additional requirements, measures and recommendations for design, erection and verification of all types of low-voltage electrical installation according to IEC 60364-1:2005, Clause 11, including local production and/or storage of energy in order to ensure compatibility with the existing and future ways to deliver electrical energy to current-using equipment or to the public network by means of local sources. Such electrical installations are designated as prosumer's electrical installations (PEIs).

A newly published part of the HD 60364 series that is applicable to domestic BESS in connection with for example a PV installation is HD 60364-8-2 (see Table A 3). It applies to prosumer's electrical installations. A prosumer is an entity or party which can be both a producer and consumer of electrical energy. BS 7671 has not yet been updated with a similar part as HD 60364-8-2.

Standards for grid connectivity

When connecting micro-generators (such as electric storage devices) to the GB public Low Voltage Distribution Network, a specific procedure must be followed. The procedure, that included both type testing and registration, is described in G83/2 and G98/1 (see Table A 4). G98/1 is an update of G83/2 that came into effect on 16 June 2019 for micro-generators commissioned on or after that date.

Table A 4: Grid connectivity standards

Standard #	Name	Pub. year	Scope
G83/2	Recommendations for the Connection of Type Tested Small-scale Embedded Generators (Up to 16A per Phase) in Parallel with Low-Voltage Distribution Systems (Withdrawn and superseded by G98/1 on 17 May 2019).	2018	This Engineering Recommendation provides guidance on the technical requirements for the connection of Type Tested Small-Scale Embedded Generators in parallel with public low-voltage distribution networks.

G98/1	Requirements for the connection of Fully Type Tested Micro-generators (up to and including 16 A per phase) in parallel with public Low Voltage Distribution Networks on or after 17 May 2019.	2018	This Engineering Recommendation provides guidance on the GB technical requirements for the connection of Micro-generators in parallel with public Low Voltage Distribution Networks. The requirements set out in this Engineering Recommendation are in addition to those of European standard EN 50438 which should be complied with in full.
BS EN 50549-1	Requirements for generating plants to be connected in parallel with distribution networks. Connection to a LV distribution network. Generating plants up to and including Type B.	2019	This document specifies the technical requirements for the protection functions and the operational capabilities for generating plants, intended to operate in parallel with LV distribution networks. BS EN 50549-1 replaces BS EN 50438:2013.

Model codes for electrical installations on the US market

Local electrical safety, building safety and fire safety legislations are based on US model codes. Local jurisdictions adopt model codes such as the National Electric Code (NEC), NFPA 1: Fire Code and International Fire Code (IFC) as local legislation (see Table A 5). These model codes have changed during recent years with respect to electric energy storage systems. Specific sections or chapters have been created to simplify the interpretation of the codes.

NEC is a model code for the safe installation of electrical wiring and equipment in the United States. It is developed by the National Fire Protection Association (NFPA) and adopted in 50 states. The requirements for energy storage systems are found in article 706. Currently, the article applies to all permanently installed energy storage systems operating at over 50 V AC or 60 V DC that may be stand-alone or interactive with other electric power production sources. In the draft version of the next edition, the article has been changed to apply to all energy storage systems (ESS) having a capacity greater than 1 kWh that may be stand-alone or interactive with other electric power production sources.

NFPA 1 and IFC are model codes for fire safety. Chapter 52 in NFPA 1 and section 1206 in IFC deal with electric energy storage systems. Only lithium-ion battery systems of 20 kWh or higher are regulated in the current versions of the codes. Most domestic BESSs are therefore not within the scope of the code. It is required in the two codes that storage batteries shall be listed in accordance with UL 1973 (see Table A 12) and pre-packaged and pre-engineered stationary battery systems shall be listed in accordance with UL 9540 (see Table A 11).

Table A 5: Model fire codes for US

Code #	Name	Pub. year	Scope
US National Electric Code (NEC)	NFPA 70	2017	The code is a regionally adoptable standard for the safe installation of electrical wiring and equipment in the United States.
NFPA 1	Fire code	2018	The purpose of the Code is to prescribe minimum requirements necessary to establish a reasonable level of fire and life safety and property protection form the hazards created by fire, explosion and dangerous conditions.
IFC	International fire code	2018	The code applies to new and existing structures and premises in matters related to occupancy and maintenance for the protection of lives and property from fire.

The National Fire Protection Association (NFPA), which develops NFPA 1 and NEC, has developed a standard for stationary energy storage systems. The standard will serve as a reference in future editions of NEC, NFPA 1 and IFC. The standard is called NFPA 855 (see Table A 6).

Table A 6: NFPA standard 855 for stationary energy storage systems

Standard #	Name	Pub. year	Scope
NFPA 855	Standard for the installation of stationary energy storage systems	2020	This standard applies to the design, construction, installation, commissioning, operation, maintenance, and decommissioning of stationary energy storage systems (ESS), including mobile and portable ESS installed in a stationary configuration. This standard provides the minimum requirements for mitigating the hazards associated with ESS.

In the current version of NFPA 855, a separate chapter has been developed for domestic energy storage systems. Energy storage systems installed in one or two dwellings or townhouse units shall comply with the requirements in chapter 15. One of requirements found in this chapter is that energy storage system of 1 kWh or greater in maximum stored energy shall be listed and labelled in accordance with UL 9540 (see **Error! Reference source not found.**). UL 9540 deals with the system aspects of electrical energy storage systems and reference specific UL standards for components used in the systems such as UL 1973 for lithium-ion batteries. This will directly affect most domestic BESS manufacturers. Another requirement is that domestic BESSs shall only be installed in the following locations:

- In attached garages separated from the dwelling unit living areas and sleeping units in accordance with the local building code.
- In detached garages and detached accessory structures.
- Outdoors on exterior or on the ground located a minimum of 914 mm from doors to windows.
- In enclosed utility closets and storage or utility spaces.

According to the standard, energy storage systems are not allowed to be installed in living areas of dwelling units or in sleeping units other than within utility closets and storage or utility spaces. Currently, there is no such similar requirements in BS 7671.

Safety standards for electrical energy storage systems

IEC technical committee 120 is working on developing normative documents dealing with the system aspects of electrical energy storage systems. The standards and technical specifications that have been published up to May 2020 are shown in Table A 8. The IEC versions of the standards have so far been adopted by CENELEC as EN standards and by BS as national standards.

More parts of the IEC 62933 series are under development. The draft versions of these standards are shown in Table A 7.

Table A 7: Standards and technical specifications under development by IEC TC 120

Standard #	Name	Forecasted Pub. year	Scope
IEC TS 62933-2-2	Electric Energy Storage Systems; Part 2-2: Unit parameters and testing methods – Applications and Performance testing.	2022	This part of IEC 62933 focuses on developing duty cycles and identifying relevant performance metrics for grid applications and developing performance testing methods and procedures for EES systems.
IEC TS 62933-3-2	Electric Energy Storage Systems: Part 3-2: Planning and performance assessment of electrical energy storage systems - Additional requirements for	2022	This part of IEC 62933 focuses on additional requirements for power intensive and for renewable

	power intensive and for renewable energy sources integration related applications.		energy sources integration related applications.
IEC TS 62933-3-3	Electrical Energy Storage (EES) systems - Part 3-3: Planning and performance assessment of electrical energy storage systems - Additional requirements for energy intensive and backup power applications.	2022	This part of IEC 62933 focuses on additional requirements for energy intensive and backup power applications.
IEC TR 62933-4-200	ELECTRICAL ENERGY STORAGE (EES) SYSTEMS Part 4-200: Guidance on environmental issues - Greenhouse gas (GHG) emission reduction by electrical energy storage (EES) systems.	2021	This part of IEC 62933 focuses on greenhouse gas (GHG) emission reduction.
IEC 62933-4-2	Electric Energy Storage System part 4-2- environment impact assessment requirement for electrochemical based systems failure.	2023	This part of IEC 62933 focuses on environment impact assessment requirement for electrochemical based systems failure.
IEC 62933-4-3	Electrical energy storage (EES) systems; part 4-3: – The protection requirements of BESS according to the environmental conditions and location types.	2023	This part of IEC 62933 focuses on the protection requirements of BESS according to the environmental conditions and location types.
IEC 62933-4-4	Electrical energy storage (EES) systems- Part 4-4: Environmental requirements for BESS using reused batteries in various installations and aspects of life cycles.	2023	This part of IEC 62933 focuses on environmental requirements for BESS using reused batteries in various installations and aspects of life cycles.
IEC 62933-5-3	Electrical energy storage (EES) systems Part 5-3: Safety requirements for electrochemical based EES systems considering initially non-anticipated modifications - partial replacement, changing	2023	This part of IEC 62933 focuses on safety requirements for electrochemical based EES systems considering initially non-anticipated modifications - partial replacement, changing

	application, relocation and loading reused battery.		application, relocation and loading reused battery.

Table A 8: Standards and technical specifications published by IEC TC 120

Standard #	Name	Pub. year	Scope
BS EN 62933-1	Electrical energy storage (EES) systems - Part 1: Vocabulary.	2018	This part of IEC 62933 defines terms applicable to electrical energy storage (EES) systems including terms necessary for the definition of unit parameters, test methods, planning, installation, safety and environmental issues.
BS EN 62933-2-1	Electrical energy storage (EES) systems - Part 2-1: Unit parameters and testing methods - General specification.	2018	This part of IEC 62933 focuses on unit parameters and testing methods of EES systems.
IEC TS 62933-3-1	Electrical energy storage (EES) systems - Part 3-1: Planning and performance assessment of electrical energy storage systems - General specification.	2018	This part of IEC 62933 is applicable to EES systems designed for grid-connected indoor or outdoor installation and operation. This document considers necessary functions and capabilities of EES systems test items and performance assessment methods for EES systems requirements for monitoring and acquisition of EES operating parameters exchange of system information and control capabilities required
IEC TS 62933-4-1	Electrical energy storage (EES) systems - Part 4-1: Guidance on environmental issues - General specification.	2017	This part of IEC 62933, which is a Technical Specification, describes environmental issues associated with electrical energy storage systems

			(EES systems), and presents guidelines to address the environmental impacts to and from EES systems including the impacts to humans due to chronic exposure associated with the mentioned environmental impacts.
IEC TS 62933-5-1	Electrical energy storage (EES) systems - Part 5-1: Safety considerations for grid-integrated EES systems - General specification.	2017	This part of IEC 62933, which is a Technical Specification, specifies safety considerations (e.g. hazards identification, risk assessment, risk mitigation) applicable to EES systems integrated with the electrical grid.
IEC 62933-5-2	Electrical energy storage (EES) systems Part 5-2: Safety requirements for grid integrated EES systems - electrochemical based systems.	2020	This part of 62933 primarily describes safety aspects for people and, where appropriate, safety matters related to the surroundings and animals for grid connected energy storage systems where an electrochemical storage subsystem is used.

IEC 62933-5-2 addresses safety risks on a system level specifically related to energy storage systems where an electrochemical storage subsystem is used. The safety requirements in IEC 62933-5-2 are applicable to domestic BESSs. The standard follows the same structure as the technical specification IEC TS 62933-5-1. Although the safety of individual subsystems is generally covered by international standards, the risks associated with combining battery subsystems and any electrical subsystems are not always covered. IEC 62933-5-2 is trying to cover these risks. It is required that a risk analysis of the BESS shall be carried out and the risk scenarios shall include all interactions between subsystems. Examples of scenarios are:

- Propagation from a battery subsystem(s) to the other.
- Propagation form non-battery subsystems.
- Simultaneous troubles of several subsystems.

IEC 62933-5-2 also includes a chapter with examples of system tests. It is mentioned in the first edition of the standard that a system test program for domestic BESSs (indoor use) needs to be addressed in a different manner than a large complex utility system (outdoor). According to the standard, a mass-produced domestic BESS in a single enclosure would be evaluated in a similar way to an appliance in that it would be subjected to a type test program, with factory acceptance testing upon production before leaving the factory and perhaps some minor site acceptance testing upon installation.

It is required at the subsystem level, that all integrated battery energy storage subsystems shall comply with appropriate safety standards. In the first edition of IEC 62933-5-2, it is required that lithium-ion battery subsystems shall comply with IEC 62619. It is likely in future versions of IEC 62933-5-2 that lithium-ion battery subsystems should comply with IEC 62619, IEC 62485-5 and IEC 63056.

- IEC 62619 is a battery safety standard for industrial lithium-ion batteries (see Table A 12).
- IEC 62485-5 is currently under development (see Table A 9). It deals with safety requirements for the safe operation of stationary lithium-ion batteries in an installation. It will be part of the same series as BS EN IEC 62485-1 and BS EN IEC 62485-2 that are used for lead-acid and nickel cadmium battery installations (see Table A 10). IEC 62485-5 will deal with specific risk for stationary lithium-ion battery installations.
- IEC 63056 has recently been published (see Table A 13). It includes specific safety requirements for lithium-ion batteries used in Electrical Energy Storage Systems under the assumption that the battery has been tested according to IEC 62619.

Table A 9: IEC standards under development for battery installations

Standard #	Name	Forecasted Pub. year	Scope
IEC 62485-5	Safety requirements for secondary batteries and battery installations - Part 5: Safe operation of stationary lithium-ion batteries.	2020	This part of the IEC 62485 applies to the installation of one or more stationary secondary batteries having a maximum aggregate voltage of d.c. 1500 V (nominal) and describes the principal measures for protections during normal operation or those that can be expected under fault conditions against hazards generated from: – electricity, – short circuits, – electrolyte, – gas emission, – fire, – explosion.

Table A 10: BS EN IEC standards for battery installations

Standard #	Name	Pub. year	Scope

BS EN IEC 62485-1	Safety requirements for secondary batteries and battery installations - Part 1: General safety information.	2018	This Part of IEC 62485 specifies the basic requirements for secondary batteries and battery installations. The requirements regarding safety, reliability, life expectancy, mechanical strength, cycle stability, internal resistance, and battery temperature, are determined by various applications, and these, in turn, determine the selection of the battery design and technology. In general, the requirements and definitions are specified for lead-acid and nickel-cadmium batteries. For other battery systems with aqueous electrolyte, the requirements may be applied accordingly.
BS EN IEC 62485-2	Safety requirements for secondary batteries and battery installations - Part 2: Stationary batteries.	2018	This part of the IEC 62485 applies to stationary secondary batteries and battery installations with a maximum voltage of DC 1 500 V (nominal) and describes the principal measures for protections against hazards generated from electricity, gas emission and electrolyte. It covers lead-acid and NiCd / NiMH batteries.

Other international system standards for electric energy storage systems are found in **Error! Reference source not found.**. UL 9540 is used on the North American market. UL 9540 is not technology specific; it deals with electrochemical, chemical, mechanical and thermal storage technologies. It references UL 1973 (Table A 12) for lithium-ion batteries and UL 1741 (see Table A 14) for the inverter. UL 9540A is a test method to evaluate the fire characteristics of a BESS. It is referenced in the current version of UL 9540 and is required for systems for installation in residential dwellings.

VDE-AR-E-2510-2 is a German standard that is often used on the German market. It is not technology specific. It references VDE and DIN-EN standards for each component. It references VDE-AR-E-2510-50 for lithium-ion batteries (Table A 12).

Both UL 9540 and VDE-AR-E-2510-2 helps the manufacturers to identify risks on a system level and the applicable standards to which each component needs to comply. Until recently, no such similar BS or EN standards existed. However, with the publication IEC 62933-5-2 and the possible future adoption of this standard as a BS standard, the manufacturer will have better guidance.

Table A 11: Electrical energy storage systems standards used internationally

Standard #	Name	Pub. year	Scope
UL 9540	Standard for Energy Storage Systems and Equipment.	2020	This standard covers energy storage systems that are intended to receive electric energy and then to store the energy in some form so that the energy storage system can provide electrical energy to loads or to the local/area electric power system (EPS) up to the utility grid when needed. The types of energy storage covered under this standard include electrochemical, chemical, mechanical and thermal.
UL 9540A	Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems.	2019	The requirements in the document evaluate the fire characteristics of a BESS that undergoes thermal runaway. The data generated will be used to determine the fire and explosion protection required for an installation of a BESS.
VDE-AR-E-2510-2	Stationary electrical energy storage systems intended for connection to the low voltage grid.	2015	This VDE application guide specifies the safety requirements for the planning, erection, operation, disassembly and disposal of stationary energy storage systems connected to the low voltage grid. Thus, it specifies those grid connection requirements to be fulfilled by installation companies which have not been specified in DIN EN 50272-2.

Safety standards for stationary lithium-ion batteries

There exist basically two lithium-ion battery safety standards that have been adopted by BS; BS EN 62619 and BS EN 62133-2. Most domestic BESS manufacturers test their lithium-ion batteries according to BS EN 62619 (see Table A 12). It is a battery safety standard for industrial lithium-ion batteries which covers various industrial applications. In contrast to BS EN 62133-2 that is used for portable lithium-ion batteries, BS EN 62619 includes functional safety requirements and tests on a battery system level and a thermal runaway propagation test. It is therefore often recommended to apply BS EN 62619 instead of BS EN 62133-2 for the lithium-ion battery part of domestic energy storage systems.

There are also other standards that are used in other markets. Two of them are:

- VDE-AR-E-2510-50 is a German standard which has some similarities with BS EN 62619.
- UL 1973 is a safety standard for batteries used for stationary applications used in the North American market. In contrast to BS EN 62619, UL 1973 considers single component failures in many of the tests. BS EN 62619 considers single component failure only in the mandatory risk analysis.

Table A 12: Standards for lithium-ion batteries used in electric energy storage systems

Standard #	Name	Pub. year	Scope
BS EN 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	This document specifies requirements and tests for the safe operation of secondary lithium cells and batteries used in industrial applications including stationary applications. Electrical safety is included only as a part of the risk analysis of Clause 8. In regard to details for addressing electrical safety, the end use application standard requirements have to be considered. This document applies to cells and batteries.
VDE-AR-E-2510-50	Stationary battery energy storage systems with lithium batteries - Safety requirements.	2017	The application guide VDE-AR-E 2510-50 specifies the safety requirements for stationary battery energy storage systems (BESSs) with lithium batteries. This application guide applies only for battery energy storage systems (BESS) with batteries based on Li-ion cells.
BATSO 02	Manual for Evaluation of Energy Systems – Secondary Lithium Batteries Part 2: Stationary Batteries.	2014	This document specifies important battery requirements and testing conditions for secondary lithium batteries used in stationary applications.
UL 1973	Standard for Batteries for Use in Stationary, Vehicle	2018	These requirements cover battery systems as defined by

	Auxiliary Power and Light Electric Rail (LER) Applications.		this standard for use as energy storage for stationary applications such as for PV, wind turbine storage or for UPS, etc. applications. These systems shall be installed in accordance with NFPA 70, C22.1, or other applicable installation codes.

BS EN 62619 covers various applications and therefore includes requirements which are common and minimum to the applications. To cover specific lithium-ion battery risks for electric energy storage systems, IEC has recently been published IEC 63056 (see Table A 13). It includes specific safety requirements for lithium-ion batteries used in electrical energy storage systems under the assumption that the battery has been tested according to BS EN 62619. IEC 63056 includes for example electrical safety requirements and tests, since electrical safety is included only as a part of a risk analysis in BS EN 62619.

Table A 13: IEC Standard recently published for lithium-ion batteries used in electric energy storage systems

Standard #	Name	Forecasted Publication year	Scope
IEC 63056	Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries for use in electrical energy storage systems.	2020	This international standard specifies requirements and tests for the product safety of secondary lithium cells and batteries used in electrical energy storage systems with a maximum voltage of DC 1500 V (nominal).

Safety standards for lithium-ion cells

Evaluation of batteries requires that the single cells used must meet the relevant safety standard.

It is common that cell manufacturers test their cells according to standards such as BS EN 62619 and UL 1642 (Table A 14). When testing according to BS EN 62619, the single cell tests are required for both the battery and the single cells they contain.

For the North American market, batteries are evaluated to UL 1973, while one of the options to demonstrate safety compliance of single cells is UL 1642.

Both BS EN 62619 and UL 1642 include minimum requirements and abuse conditions that a lithium-ion cell should be able to withstand independent of which battery design it is used in.

Table A 14: BS EN and international standards for lithium-ion cells

Standard #	Name	Pub. year	Scope
BS EN 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	This document specifies requirements and tests for the safe operation of secondary lithium cells and batteries used in industrial applications including stationary applications. Electrical safety is included only as a part of the risk analysis of Clause 8. In regard to details for addressing electrical safety, the end use application standard requirements have to be considered. This document applies to cells and batteries.
UL 1642	Standard for Lithium Batteries.	2012	These requirements cover primary (non-rechargeable) and secondary (rechargeable) lithium batteries for use as power sources in products. These batteries contain metallic lithium, or a lithium alloy, or a lithium ion, and may consist of a single electrochemical cell or two or more cells connected in series, parallel, or both, that convert chemical energy into electrical energy by an irreversible or reversible chemical reaction.

Functional safety standards for control and battery management system

Both BS EN 62619 and UL 1973 include functional safety requirements on the battery management system (BMS). BS EN 62619 requires, for example, that reliance on electric, electronic and software controls and systems for critical safety shall be subjected to analysis for functional safety.

Standards that are often used in the evaluation of functional safety are shown in Table A 15.

Table A 15: Functional safety standards applicable for control and battery management system

Standard #	Name	Pub. year	Scope

BS EN 61508 series	Functional safety of electrical/electronic/programmable electronic safety-related systems.	2010	This international standard covers those aspects to be considered when electrical /electronic/ programmable electronic (E/E/PE) systems are used to carry out safety functions.
BS EN 60730-1	Automatic electrical controls for household and similar use.	2016	This document applies to automatic electrical controls for use in, on, or in association with equipment for household and similar use. The equipment may use electricity, gas, oil, solid fuel, solar thermal energy, etc., or a combination thereof.
UL 991	Standard for Tests for Safety-Related Controls Employing Solid-State Devices.	2004	These requirements apply to controls that employ solid-state devices and are intended for specified safety-related protective functions.
UL 1998	Standard for Software in Programmable Components.	2013	This standard applies to non-networked embedded software residing in programmable components performing safety-related functions whose failure is capable of resulting in a risk of fire, electric shock, or injury to persons

For BESSs connected to the internet, IEC 62933-5-1 (see Table A 8) recommends a risk analysis for cyber security could be made. Table A 16 shows some example of cyber security standards.

Table A 16: Examples of cyber security standards

Standard #	Name	Pub. year	Scope
UL 2900-1	Standard for Safety, Software Cybersecurity for Network-Connectable Products, Part 1: General Requirements.	2017	This standard applies to network-connectable products that shall be evaluated and tested for vulnerabilities, software weaknesses and malware.
IEC 62443 series	Industrial communication networks - Network and system security.	2009-2019	The IEC 62443 series are multi-industry standards listing cybersecurity protection methods and techniques.

Lithium-ion battery transportation safety

Transportation of lithium-ion batteries needs to comply with transportation safety regulations. Transportation safety regulations are separate from the electrical safety regulations and they are part of the dangerous goods regulations.

These regulations consider all means of transport such as:

- Sub-supplier to end product manufacturer, manufacturer to distributor.
- Battery in or outside of product.
- In-field/In-use.
- Product returns.
- Disposal/recycling.

UN Model Regulations (UN Recommendations on the Transport of Dangerous Goods – Model Regulations) provide a framework for transportation requirements and packing guidelines for all modes of transportation. UN Manual of Tests and Criteria is referenced in the UN Model Regulations. Part III Section 38.3 of the manual addresses lithium-ion battery testing requirements that are used to comply with the dangerous goods regulations. It is required that the lithium-ion battery needs to be tested as transported.

Safety standards for power electronic converter systems and inverters

Examples of applicable standards for power electronic converter systems are shown in Table A 17: Standards for inverters in BESSs. EN 62477-1, EN 62109-1 and EN 62109-2 are harmonized standards with the Low Voltage Directive (LVD), which means that they can be used to show compliance with the directive. As seen in Table 2, most manufacturers use BS EN 62109-1 and BS EN 62109-2 to show compliance to the directive for the inverter. BS EN 62477-1 could be used to show compliance to the Low Voltage Directive (LVD) for both the battery subsystem and the power conversion subsystem if needed.

Standard for electromagnetic compatibility (EMC)

BS EN IEC 61000-6-1 and BS EN 61000-6-3, shown in Table A 18, are often used for domestic BESSs to show compliance with the EMC directive. It is also recommended in the draft version of IEC 62485-5-2 (see Table A 8) that tests on the DC lines for emission and immunity shall be performed, even if these tests are only optional or informative in the used EMC standards. The draft of IEC 62485-5-2 also reference IEC 61000-6-7, IEC 61000-1-2 and IEC 60364-4-44 in the system validation and testing section.

Table A 17: Standards for inverters in BESSs

Standard #	Name	Pub. year	Scope
BS EN 62477-1	Safety requirements for power electronic	2016	This part of IEC 62477 applies to Power Electronic Converter

	converter systems and equipment – Part 1: General.		Systems (PECS) and equipment, their components for electronic power conversion and electronic power switching, including the means for their control, protection, monitoring and measurement, such as with the main purpose of converting electric power, with rated system voltages not exceeding 1 000 V a.c. or 1 500 V d.c.
BS EN 62109-1	Safety of power converters for use in photovoltaic power systems – Part 1: General requirements.	2010	This part of IEC 62109 applies to the power conversion equipment (PCE) for use in Photovoltaic (PV) systems where a uniform technical level with respect to safety is necessary. This standard defines the minimum requirements for the design and manufacture of PCE for protection against electric shock, energy, fire, mechanical and other hazards.
BS EN 62109-2	Safety of power converters for use in photovoltaic power systems –Part 2: Particular requirements for inverters.	2011	This Part 2 of IEC 62109 covers the particular safety requirements relevant to d.c. to a.c inverter products as well as products that have or perform inverter functions in addition to other functions, where the inverter is intended for use in photovoltaic power systems.
UL 1741	Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources.	2010	This standard covers inverters, converters, charge controllers, and interconnection system equipment (ISE) intended for use in stand-alone (not grid-connected) or utility-interactive (grid-connected) power systems. Utility-interactive inverters, converters, and ISE are intended to be operated in parallel with an electric power system (EPS) to supply power to common loads.

Table A 18: EMC standards applicable for domestic BESSs

Standard #	Name	Pub. year	Scope
BS EN IEC 61000-6-1	Electromagnetic compatibility (EMC). Generic standards. Immunity standard for residential, commercial and light-industrial environments.	2019	This generic EMC immunity standard is applicable if no relevant dedicated product or product family EMC immunity standard exists. This standard applies to electrical and electronic equipment intended to be operated in: residential locations, both indoor and outdoor, commercial, public and light industrial locations, both indoor and outdoor.
BS EN 61000-6-3	Electromagnetic compatibility (EMC). Generic standards. Emission standard for residential, commercial and light-industrial environments.	2007 (A1: 2011)	This generic EMC emission standard is applicable if no relevant dedicated product or product family EMC emission standard exists. This standard applies to electrical and electronic equipment intended to be operated in: residential locations, both indoor and outdoor, commercial, public and light industrial locations, both indoor and outdoor.
BS EN 61000-1-2	Electromagnetic compatibility (EMC). General. Methodology for the achievement of functional safety of electrical and electronic systems including equipment with regard to electromagnetic phenomena.	2016	This part of IEC 61000 establishes a methodology for the achievement of functional safety only with regard to electromagnetic phenomena. This methodology includes the implication it has on equipment used in such systems and installations.
BS EN 61000-6-7	Electromagnetic compatibility (EMC) - Part 6-7: Generic standards - Immunity requirements for equipment intended to perform functions in a safety-related system (functional safety) in industrial locations.	2014	This part of IEC 61000 is intended to be used by suppliers when making claims for the immunity of equipment intended for use in safety-related systems against electromagnetic disturbances. This part of IEC 61000 applies to electrical and electronic equipment intended for use in safety-related systems and that is intended to comply with the requirements of IEC

			61508 and/or other sector-specific functional safety standards, and intended to be operated in industrial locations as described in 3.1.15.
IEC 60364-4-44	Low-voltage electrical installations - Part 4-44: Protection for safety - Protection against voltage disturbances and electromagnetic disturbances.	2007 (AMD: 2018)	The rules of this Part of IEC 60364 are intended to provide requirements for the safety of electrical installations in the event of voltage disturbances and electromagnetic disturbances generated for different specified reasons.

Guidelines and codes

Several organizations have developed guidelines and codes of practice for BESSs. Table A 19 shows some examples.

Table A 19: Guidelines and codes of practice for electric and BESSs

Organization	Name	Pub. year	Scope
IET	Code of Practice for Electrical Energy Storage Systems.	2017	The purpose of this code of practice is to provide a reference to practitioners on the safe, effective and competent application of electrical energy storage systems.
Australian industry associations	Best Practice Guide: Battery Storage Equipment – Electrical Safety Requirements.	2018	This guide provides safety criteria for battery storage equipment that contains lithium as part of the energy storage medium.
German Solar Industry Association	Safety Guidelines – Li-ion Home Storage Systems.	2014	This document identifies safety objectives for battery storage systems that function as stationary home storage systems and are based on rechargeable lithium-ion cells (secondary lithium-ion cells), with and without incorporation of converters, for example, those used in

			combination with photovoltaic applications.
IEEE	IEEE P2030: IEEE Draft Guide for Design, Operation, and Maintenance of Battery Energy Storage Systems, both Stationary and Mobile, and Applications Integrated with Electric Power Systems.	2019	This document provides alternative approaches and practices for design, operation, maintenance, integration and interoperability, including distributed resources interconnection, of stationary or mobile battery energy storage systems (BESS) with the electric power system(s) (EPS) at customer facilities, at electricity distribution facilities or at bulk transmission electricity facilities.

This publication is available from: www.gov.uk/government/publications/domestic-battery-energy-storage-systems

If you need a version of this document in a more accessible format, please email enquiries@beis.gov.uk. Please tell us what format you need. It will help us if you say what assistive technology you use.