Office for Product Safety & Standards

A Study on the Safety of Second-life Batteries in Battery Energy Storage Systems

Final report

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Acknowledgements

Executive summary

Electrical energy storage will be a critical source of flexibility needed to transform and decarbonise the energy system. These systems allow for the storage of energy for times when it is needed and increase the flexibility of the grid, which is key for integrating variable renewable generation. From a consumer perspective, domestic lithium-ion battery energy storage systems (DLiBESS) are becoming an attractive option, particularly when installed alongside onsite generation such as solar photovoltaic (PV), enabling the consumer to maximise the use of this generation and to buy and sell electricity at times that are financially advantageous. This is particularly beneficial when used in conjunction with Demand Side Response (DSR).

Although few incidents of thermal runaway with DLiBESS are known in the public domain, such an event could present hazards such as fire, toxic gas release or explosion. The safety risks, best practice and standards associated with the use of new lithium-ion batteries (LiBs) in domestic systems are covered in BEIS research paper 2020/037, "*Domestic battery energy storage systems: a review of safety risks*" [1].

The current study follows on from this, as it addresses the use of second-life lithium-ion batteries in DLiBESS driven by the significant increase in the availability of second-life electric vehicle (EV) batteries resulting from the global drive to decarbonisation. However, there is a concern that second-life LiBs may have a greater risk of failure if steps are not taken to adequately mitigate this risk. Therefore, the aim of this study is to improve the evidence base available to OPSS on the safety risks and hazards associated with the application of second-life lithium-ion batteries in domestic LiBESS and measures to mitigate these, including an assessment of best practice and standards. This report contains findings from a literature review and is supplemented by consultations with key stakeholders.

The market

The market for second-life DLiBESS (SLDLiBESS) is difficult to predict which was evident by the absence of detailed market information. While a number of stakeholders consulted as part of this study use second-life batteries in their LiBESS, these are predominantly for industrial applications and evidence suggests there is currently limited use in domestic systems. Therefore, in order to assess the potential market for SLDLiBESS, the following drivers and barriers were reviewed as reasonable indicators:

- **The market for DLiBESS.** Market analysis suggests that the UK DLiBESS market is a nascent but growing industry, with estimated capacity at 38 MWh in 2019 expected to rise to between 128 – 339 MWh by 2024 [2]. Consumer drivers are likely to be maximising use of onsite generation, such as solar, in addition to buying and selling electricity. This should be considered in light of rising electricity costs and the falling costs of LiBs.

- **Environmental and economic drivers for second-life LiBs.** The extraction and processing of the metals required by LiBs is both expensive and harmful to the environment. Additionally, it is estimated that there could be 75,000 to 105,000 end of first-life (EoFL) EV LiBs in the UK by 2025, which represent potential environmental and safety waste hazards. In contrast, reuse, remanufacture or repurposing could extend battery life by 7 – 10 years, minimising waste and delaying or reducing materials recovery which is currently both energy intensive and limited in capacity.

- **Availability of second-life LiBs.** While the projected surplus of second-life LiBs is good news for the DLiBESS industry, the latter is unlikely to soak up the surplus

and there will have to be significant innovation and investment in materials recovery. This will likely be driven by material supply and/or regulation, with the 2022 EU Batteries Regulation proposing to significantly increase the recovery of certain metals from LiBs in addition to requirements to incorporate certain levels of these recyclates into new LiBs. While likely to drive materials recovery, this could be at the expense of second-life.

- **Price of second-life LiBs.** It is currently both costly and labour intensive to test and triage EoFL batteries due to a lack of standardisation among EV OEMs. In addition, the falling cost of new LiBs means the economic incentive for reuse and repurposing may become less attractive.

Risks and hazards

The hazards represented by LiBs can be severe if they are not properly mitigated. The hazards associated with second-life LiBs are broadly the same as for new LiBs, but the probability of failure may be higher with the former due to the effects of ageing and unknown stress and/or abuse during the LiBs first life application. However, this remains an ongoing area of research and there is currently insufficient information available to determine either the likelihood of an age-related failure or the effect of that failure with confidence.

The capacity loss of LiBs is generally considered to be linear, with EoFL typically around 75-80% state of health (SoH) and final end-of-life around 50-60% SoH. However, at some point there is a change in and/or an additional ageing mechanism which leads to an increased ageing rate. The time at which this occurs is referred to as the "knee" where severe and potentially dangerous deterioration is expected to occur and the battery has reached its final end-of-life. Currently this point is difficult to predict, but can occur at a higher SoH than expected. Cycling at normal rates or calendar ageing does not have a significant impact on safety; however, cycling at low temperatures or high rates can have a detrimental effect upon stability and can significantly reduce the temperature at which thermal runaway occurs and consequently increase the risk of thermal runaway. In addition, this is shown to increase the risk of internal short circuits and joule heating.

It is for this reason, and due to the potential variance of SoH between EoFL LiBs (including within the same pack), that a sample of second-life LiBs should not be taken to be representative of the batch. Therefore, the safety of second-life LiBs cannot be reliably assured by type tests, which form the basis of all current international and European standards. Instead, an assessment is required for each LiB prior to use in a second-life application, including SLDLiBESS.

Best practice and standards

The re-purposing of LiBs is a nascent global market which has led to some uncertainty amongst respondents in terms of the codes, standards and regulations governing their testing, fitness for purpose, and transport. There are currently no UK or European standards specifically for second-life LiBs; however, both IEC 63330 and IEC 63338 are being developed to address this gap. IEC 63330 will specify the procedure for assessing the safety of second-life LiBs to be employed in applications other than that of their first life, and IEC 63338 provides high-level guidance on the safe and environmentally benign re-use of LiBs. Additionally, the EU Batteries Regulation contains requirements for second-life LiBs, including for first-life data to be made available in the battery management system (BMS) to facilitate re-use. Outside of the UK and Europe, UL 1974 (Standard for Evaluation for Repurposing Batteries) covers the sorting and grading process of LiBs that are intended for a repurposed use application.

Current practices include a variety of methods to measure state-of-health and/or reliance on detailed information retained in the BMS employed during first life (i.e. the EV BMS). The engagement of EV OEMs in the latter has yet to be assessed, but is a critical factor. This information may include parameters such as: extreme values of temperature, charge and discharge current and charge & discharge voltage, details of insulation failure, accidents and storage conditions, total times or number of instances at extremes or out of specification, total number of charges and discharges, total times or numbers under charge and under discharge and total number or type of error messages. Gateway testing to assess the health of second-life LiBs includes: measuring capacity, internal resistance and self-discharge and performing a discharge/charge cycle test. This information should then also be used to balance and match LiBs in a second-life application. However, **there is currently no widely-accepted test methodology for assessing the safety of second-life LiBs and this is a major gap in international standards.** Additionally, there remains uncertainty amongst stakeholders around the transportation of second-life LiBs.

Beyond the assessment and sorting processes discussed above, there is currently limited information available on best practice for designing LiBESS to use second-life LiBs. Additional considerations include use of a dedicated BMS for the new application, such as introducing control strategies for second-life LiBs, as well as monitoring as close to cell level as possible. The importance of monitoring at cell level was highlighted by the incident in Surprise, Arizona, and is a requirement in the German standard VDE-AR-E 2510: 2017 and DNV RP43. While both the incident and standards are applicable to new LiBs, they are particularly relevant for second-life LiBs as evidence suggests the cell-to-cell inconsistencies will increase with age.

Concluding remarks

Extensive discussions with stakeholders have revealed two opposing views on second-life batteries: firstly, that a safety framework can be put in place to allow the use of second-life LiBs in DLiBESS, so long as the full history of the batteries in their first life applications is known and/or they can be tested effectively. A second, more radical view shared by some respondents is simply that the safety of such cells can never be guaranteed, and hence that second-life LiBs should not be employed under any circumstances in DLiBESS.

Lastly, due to the fire and electrical hazards associated with LiBs, the availability of potentially untested second-life LiBs and the potential lack of knowledge (for example, with LiB ageing) and skills of consumers to mitigate the risk through testing and good system design, consideration should also be given to whether stricter requirements are needed for home-built ("DIY") DLiBESS that use second-life batteries.

Contents

Glossary

Ageing	The loss of capacity due to, e.g. loss of lithium-ions or spallation of the anodes. This can be due to use (charging and discharging) and/or sitting at open circuit (calendar ageing).
Anode	The negative electrode. In lithium-ion batteries this is most typically small particles of graphite.
ATF	Authorised treatment facility.
Battery (pack)	The complete energy storage unit consisting of a number of modules or strings.
BESS	Battery energy storage system.
BMS	Battery management system. This monitors and controls all the functions and the state-of-health of the battery.
BoL	Beginning of Life.
Calendar ageing	The changes in the cells of a LiB when in the passive state, i.e. not charging or discharging.
C-rate	The rate of charging or discharging expressed in terms of the capacity of the battery. A C-rate of 1 will charge/discharge a battery in 1 hour: thus, 1C discharge of a 60Ah battery requires 60A.
Capacity	The amount of charge stored in a battery or cell, usually specified in Amp hours (A h) or Watt hours (Wh). 1 A h = 3600 Coulombs (C).
Cathode	The positive electrode. These typically comprise lithium transition metal oxides: *e.g.* lithium nickel manganese cobalt oxide ($LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$).
Cell	The smallest unit of a battery.
Current collector	The aluminium or copper foil on which is coated the cathode and anode material, respectively.
DIY SLDLiBESS	Do-It-Yourself second life domestic lithium-ion battery energy storage system
DLiBESS	Domestic lithium-ion battery energy storage system.
DMC	Dimethylcarbonate. One of the solvents used in the electrolyte.
DSR	Demand Side Response
EC	Ethylenecarbonate. One of the solvents used in the electrolyte.
EIS	Electrochemical impedance spectroscopy.
Electrolyte	In electrochemistry, this term can refer either to the inorganic salt (*e.g.* $LiPF_6$) or to the salt + organic solvent in which it is dissolved.
End of Life (EoL)/ End of First Life (EoFL)	The point at which a battery ceases to be suitable for its current application. EoFL for automotive batteries is typically 75 – 80% State-of-Health.
End of Second-life (EoSL)	The final end of life of a lithium-ion battery, usually taken as 50 – 60% SoH.
Energy	The energy stored in a battery is specified in Watt hours (W h) or kiloWatt hours (kW h): 1 W h = 1 Amp Volt x 3600 secs = 3600 AVs = 3600 Joules.
Energy density	The energy per unit volume (litre) of battery.

EMC	Ethylmethylcarbonate. One of the solvents used in electrolyte.
EV	Electric vehicle
Galvanic cell	Usually just referred to as a cell. A device which when charged with electricity is in a higher energy state than when discharged. On discharge the chemical energy stored is released as an electrical current.
LCO cathode	Lithium Cobalt Oxide, $LiCoO_2$.
LiB	Lithium-ion Battery and general term for lithium-ion cells, modules and packs.
LFP cathode	Lithium iron (Ferrous) Phosphate, $LiFePO_4$.
LiBESS	Lithium-ion battery energy storage system.
$LiPF_6$	Lithium hexafluorophosphate
LMO cathode	Lithium Manganese Oxide e.g. $LiMn_2O_4$.
Module or string	Manufacturer-specific terms, e.g. collection of cells arranged in series and/or parallel.
MMO	Mixed metal oxide (cathode material).
NCA cathode	(Lithium) Nickel Cobalt Aluminium oxide, *e.g.* $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$.
NiCd	Nickel Cadmium
NMC cathode	(Lithium) Nickel Manganese Cobalt oxide, *e.g.* $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ (NMC 111), $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ (NMC 622).
OEM	Original equipment manufacturer.
Open circuit	The state when a battery or cell is disconnected from an external circuit.
Open Circuit Voltage (OCV)	The potential difference (voltage) across the terminals of a cell or battery when no current is allowed to flow. This can be correlated with the State of Charge (SoC).
PV	Photovoltaic (array): solar electric panels.
Reuse	Battery pack is re-used in its entirety in the same application as in first life.
Remanufacture	Selection of modules at end-of-first life and assembly into batteries or packs for second-life applications.
Repair	Battery pack is re-used in the same application as in first life, but faulty modules are replaced.
Risk	Risk = probability of hazard occurring x severity of hazard.
RUL	Remainder of Useful Life
Salt	The inorganic compound employed to produce ions in the cell. This is typically lithium hexafluorophosphate ($LiPF_6$) which dissociates in the organic solvent to produce lithium cations (positively charged ions, Li^+) and hexafluorophosphate anions (negatively charged ions, PF_6^-).
Separator	A plastic film permeable to lithium and hexafluorophosphate ions that prevents the anode and cathode from touching and causing a short circuit.
SLDLiBESS	Second-life domestic lithium-ion battery energy storage system.

Solid Electrolyte Interface (SEI)	The protective layer that forms on the anode during the first charge from reduction of the $LiPF_6$ and solvent which prevents further, explosive degradation of the electrolyte and thermal runaway.
Solvent	Mixture of organic carbonates, containing ethylene carbonate, as this is essential for the formation of the SEI. Ethylene carbonate is a solid at room temperature and other carbonates are essential to reduce viscosity.
Specific energy	The energy per kg of battery.
State of Charge (SoC)	The amount of charge stored compared to that equivalent to full charge, expressed as %.
State of Health (SoH)	To truly assess this requires the entire life history of a lithium-ion cell. However, simple algebraic expressions are often employed, the two most common being: the amount of charge stored currently when fully charged, or the internal resistance, compared to that at the beginning of the cell or battery life, expressed as %.
State-of-Safety (SoS)	A more detailed description of the state-of-health of a LiB.
ToU	Time of use billing.
Virtual Power Plant (VPP)	Grouping of DLiBESS to support the grid.
VOC	Volatile organic compounds.

1 Introduction

This document is the Final Report of the "**Study on the Safety of Second-life Batteries used in Domestic Battery Energy Storage**". The work was carried out on behalf of the Office for Product Safety and Standards (OPSS) by Newcastle University between February and November 2021.

The project commenced with in-depth research of academic, commercial and regulatory sources which was supplemented by consultations with key stakeholders. In total, representatives from over 30 organisations responded, including from electric vehicle (EV) and battery energy storage system (BESS) manufacturers/suppliers and industry associations, battery recyclers, research institutes, public and government bodies, product safety experts and standards bodies. Following assessment by OPSS and amendment, a virtual workshop was held with all respondents to test and validate the findings. This is the final report.

The study starts with an overview of the market for second-life batteries, followed by a review of hazards for lithium-ion batteries and risks specific to second-life batteries along with a description of gateway testing and other mitigating measures. It then provides a detailed analysis of the relevant codes, standards and regulations and considers best practice when using second-life batteries in battery energy storage systems.

1.1 Overview of study

Electrical energy storage is seen as a key source of flexibility which will be needed to transform and decarbonise the energy system. These systems allow for the storage of energy for a time when it is needed and increase the flexibility on the grid, which is key for integrating variable renewable generation. Electrochemical battery technology, particularly lithium-ion, is a significant contributor to UK storage capacity, with 1GW of capacity installed since 2017 and 8GW of capacity in the planning pipeline [3]. Energy storage systems can also be installed in the home, with domestic battery energy storage systems (DLiBESS) allowing the user to buy and sell electricity at times that are financially advantageous. This is particularly beneficial when used in conjunction with solar power and/or Demand Side Response (DSR). Some systems can also offer limited off-grid capability in the event of a mains power failure.

Although few incidents of thermal runaway with DLiBESS are known to date in the public domain, such an event could present hazards such as fire, toxic gas release or explosion. The safety risks, best practice and standards associated with the use of new lithium-ion batteries in domestic systems are covered in BEIS research paper 2020/037, "*Domestic battery energy storage systems: a review of safety risks*" [1]. The report found that if manufacturers and installers follow best industry practices and standards, they can significantly mitigate risks in the residential application of BESSs.

The current study follows on from this, as it addresses the use of second-life lithium-ion batteries in DLiBESS driven by the significant increase in the availability of second-life electric vehicle batteries resulting from the global drive to decarbonisation. While still considered safe and usable, their capacity is typically 75-80% that of a new battery. This reduction in capacity makes them inadequate for satisfactory car use, but the additional weight/volume:energy ratio of these used batteries is not a problem in stationary applications. It is estimated that LiBs used in second-life stationary storage applications can be of service for a further 10 years before reaching their absolute end-of-life [4].

However, there is a concern that second-life batteries may have a higher risk of failure if steps are not taken to adequately mitigate this risk, due either to the poor condition of the individual cells, the design quality of the new battery assembly, or a new duty that is

different to that for which the battery was originally intended. Additionally, there is some evidence to suggest that consumers are building their own DLiBESS using second-life modules purchased online and as EV batteries become more accessible it is foreseeable that this activity will increase.

1.2 Study objectives and scope

The aim of this study is to understand best practice in the design and installation of DLiBESS that use second-life batteries and to provide OPSS with a clear understanding of the safety risks to consumers and typical methods used by manufacturers to reduce these risks. This breaks down into the following objectives:

- **Objective 1:** Analyse the current and forecasted market for second-life batteries in DLiBESS.
- **Objective 2:** Assess the safety risks and hazards of second-life batteries.
- **Objective 3:** Review best practice and mitigating measures for the assessment of second-life batteries and the design of DLiBESS that use second-life batteries.

The following table provides an overview of the research framework, linking the three study objectives to research questions and signposting where in this report each issue is discussed.

Table 1 Study objectives and research questions

| Study Objective	Research questions	Final report section
Objective 1	What does the current and forecasted future market look like for second-life domestic LiBESS?	Sections 2 & 3
Objective 2	What are the consequences of including damaged or lower performing cells in a battery pack?	Sections 4 & 5
	What are the risks to the consumer of purchasing or building their own second-life battery?	Section 5
Objective 3	What are the safety issues that should be taken into consideration if creating a new battery pack from second-life cells?	Sections 6, 7 & 8
	How can used cells, modules and packs be individually assessed for condition, performance and safety? What will be the impact of future codes, standards and regulations?	Sections 6 & 8
	Do existing testing regimes sufficiently assure safety for the end-product?	Section 8

2 Overview of lithium-ion cells

2.1 Physical characteristics

Lithium-ion batteries (LiBs) are devices for storing electrical energy: they are secondary batteries as, once discharged, they can be recharged by supplying electricity.

The lowest unit of a LiB is the cell. Cells are combined in series and parallel to form a module or string and a number of modules or strings comprise a battery or battery pack. Cells come in three common forms, or form factors [5]: cylindrical, pouch and prismatic, see Figure 1.

Figure 1 The common lithium-ion cell form factors: (a) cylindrical, (b) pouch and (c) prismatic. © Intertek.

(a)   (b)   (c)
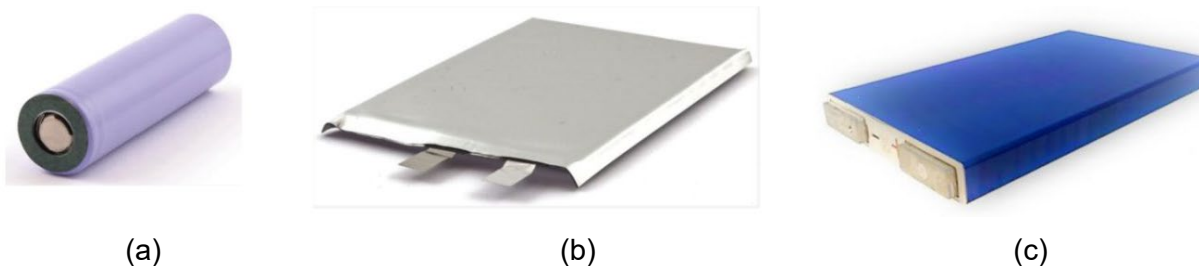
Cylindrical cells are typically 18 mm in diameter and 65 mm long (18650): other dimensions include 26650 (26 mm diameter and 65 mm long) and 21700 (21 mm diameter and 70 mm long). Prismatic cells come in a range of sizes depending upon application. Pouch cells are typically the size of an A4 or A5 sheet and about 16 mm thick. In Tesla EVs, over 7000 cylindrical cells form the battery pack: in the post-2018 Nissan Leaf, there are 8 A4 sized pouch cells per module and 24 modules per pack [6]. The number of cells in industrial LiBESS depends upon the rated energy of the cells and the system (in MWh), but as an example, the 2MW LiBESS that exploded in Arizona in April 2019 comprised 10,584 64Ah pouch cells [7]. For domestic scale LiBESS, the 13.5 kWh Tesla Powerwall 2, for example, employs 750 – 900 21700 NMC cells [8].

2.2 Applications

The first application of LiBs was in portable electronics, specifically Sony camcorders in 1991 [9], but this expanded rapidly into mobile phones and laptops using all three form factors. The next paradigm shift was the use of LiBs in EVs heralded by the first production battery EV, the Tesla Roadster in 2008 [10]. This also triggered very large-scale production of LiBs in gigafactories. Plug-in hybrid EVs were followed by the Nissan Leaf in 2010 and a significant increase in the LiB market in 2015 due to the introduction of Chinese EV buses [11]. The first LiB Energy Storage System (LiBESS) was installed in 2008 in Guadeloupe in a collaboration between SAFT, Tenesol, ADEME and EDF SEI and was actually a number of residential or domestic LiBESS (DLiBESS), consisting of 15 SAFT 11 kWh units each connected to a 2 kW photovoltaic (PV) system [12]. The first large scale (5MW) LiBESS was commissioned for Portland General Electric in 2012 [13].

2.3 Composition and electrochemistry

A LiB cell comprises two electrodes, the anode and cathode, pressed either side of a porous polymer separator soaked in electrolyte. The electrolyte is a mixture of organic compounds with an added salt, lithium hexafluorophosphate or $LiPF_6$, that dissociates in the organic mixture to produce free lithium and hexafluorophosphate ions (Li^+ and PF_6^-). The separator prevents the electrodes from touching each other, which would cause an

internal short circuit and significant Joule heating, but allows the free movement of the ions.

When fully discharged, all the lithium-ions are present inside the crystal structure of the cathode (see Figure 2) which is typically a mixed-metal oxide (MMO) such as NMC (Nickel Manganese Cobalt, $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$) or LFP (Lithium iron [Ferrous] Phosphate, $LiFePO_4$) [14]. Most LiBs employ graphite anodes and hence they are discriminated between, and the cells known by, the cathode composition (NMC; LFP; lithium manganese oxide, LMO, etc). On charging, the lithium-ions move out of the cathode, move through the electrolyte and into the anode, which is typically made up of very small particles of graphite. By definition, oxidative processes take place at the anode and reductive processes at the cathode. The anode is the graphite electrode during discharge and the mixed metal oxide is the cathode: on charging, these terms should switch (i.e. the MMO should become the anode). However, by convention, the terms retained are those specified for discharge.

Figure 2 The charge and discharge of a LiB
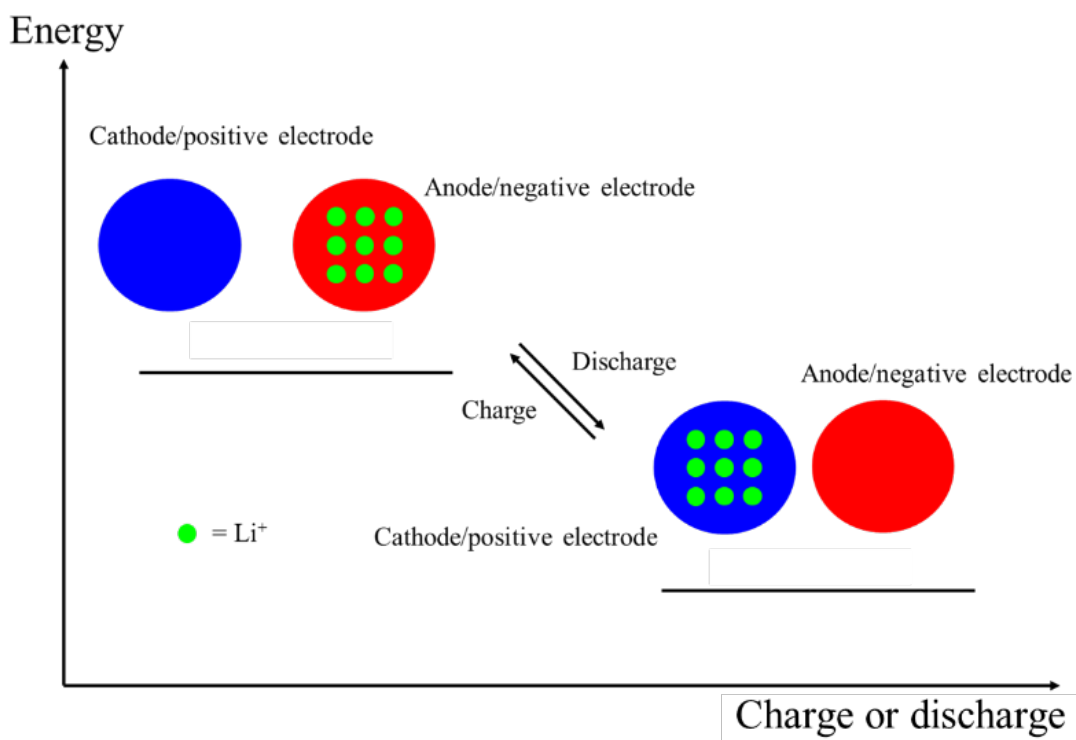
Typical separators are polyethylene, polypropylene or a combination of both. The separators typically employed in LiBs [15] are ca. 20-30 μm thick, which is about $^1/_5$ to $^1/_3$ of the thickness of a standard sheet of A4 paper: i.e. very thin, and this should be considered in the discussions later in the document concerning abuse and the consequent internal short-circuiting of anode and cathode.

LiBs have energy densities hitherto not seen for conventional batteries such as lead acid, nickel-cadmium (NiCd) etc, with EV batteries having densities [16] up to 250 Wh kg^{-1} and long cycling life.

3 The market for second-life LiBESS

The market for SLDLiBESS is difficult to predict which was evident from the absence of detailed market information. However, the DLiBESS original equipment manufacturers (OEMs) consulted during this project all held the view that the demand for domestic LiBESS in general was set to increase significantly over the next decade. This includes two EV OEMs who stated they were repurposing second-life LiBs for portable energy storage applications [17, 18] (e.g. on building sites), while only one company was repurposing these for use in SLDLiBESS [19]. The low number of existing SLDLiBESS on the market correlates with an economic analysis presented in the European ELSA project (Energy Local Storage Advanced system, 2015 - 2018) which stated that the potential market for second-life batteries for domestic use is "low" [20]. Similarly, market analysis from Zhu et al. [21] shows that while the number of industrial applications using second-life LiBs is increasing rapidly, only 3 out of the 41 projects identified were for domestic purposes.

In general, there is a lack of detailed information on the market for second-life LiBs: hence this section analyses the market for DLiBESS more broadly, along with the drivers, supply and demand for second-life EV batteries, as a reasonable indicator of the potential market for SLDLiBESS.

3.1 The market for DLiBESS

Industrial scale LiBESS are seen as the major market for second-life LiBs with the total global market predicted to be up to 2857 GWh by 2040 due to their wide application and the falling price of LiBs [22-24]. These energy storage systems have a number of functions including [25]: frequency regulation, replacing spinning reserves, voltage or reactive power support, load following, peak shaving, load management and arbitrage, and are ideal for supporting renewable energy generation and storage[1].

In general, the consumer drivers [26] behind the use of DLiBESS and SLDLiBESS[2] may include environmental concerns, but are more likely to be economic. Solar energy generation globally in 2021 was the cheapest [27] ($37/MWh) compared to wind ($40/MWh), coal ($112/MWh) and nuclear power ($163/MWh) [28]. This, when considered along with rising electricity costs [29] and falling LiB prices [30], would be expected to see a significant uptake of PV arrays combined with LiBESS to help consumers maximise the use of their onsite generation and avoid importing electricity from the grid in peak periods.

According to a study from Solar Power Europe, the UK currently ranks 3rd in Europe for the uptake of such DLiBESS after Germany and Italy, however, its share of the market was only 38 MWh in 2019 compared to 496 MWh for Germany. Further, by 2024 the UK DLiBESS capacity is expected to rise to 128 – 339 MWh, slipping to 4th in the ranking compared to 2378 – 4028 for Germany, 430 – 900 (Italy) and 242 – 435 MWh (Austria) [2]. The top 3 countries provide incentives to encourage the uptake of PV+DLiBESS systems. Instead, the UK approach for facilitating domestic storage is to remove barriers and reform markets through actions taken in the 2021 Smart Systems and Flexibility Plan [3]. For solar PV the UK's Feed-in Tariff closed to new applicants in March 2019 and was replaced by the Smart Export Guarantee (SEG) in January 2020. As a market-led mechanism, where suppliers are responsible for the setting and payment of export tariffs, SEG is designed to allow room for the market to develop options, promoting innovation and

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[1] Spinning reserves, named after the turbines employed, are coal or gas-fired power stations kept active but idling (as starting up a "cold" station can take days or even weeks) to supply rapid grid support.
[2] DLiBESS is generally used for commercial domestic systems using new cells and SLDLiBESS for commercial and Do-It-Yourself (DIY) domestic systems employing second-life cells. The latter are assembled by homeowners with lithium-ion modules or packs purchased from online suppliers.

competition as part of the transition to a smart and flexible energy system. The SEG framework is designed to maximise the benefits of solar PV and storage combinations by encouraging onsite consumption and agile, time of use tariffs. However, two DLiBESS manufacturers consulted as part of this study argued that this shift has slowed the uptake of domestic energy storage in the UK[3]: and a UK not-for-profit centre of energy expertise and market insight estimated that a PV+DLiBESS system would require a more than 20 year payback period, whilst the owner of a DLiBESS system alone would struggle to achieve any payback at all. Currently, therefore, this is a nascent market. However, electricity is easier to store than heat and the UK domestic storage market is expected to increase significantly due to owners of PV arrays retrofitting DLiBESS, homeowners wishing to exploit behind-the-meter-storage/time of use (TOU) billing and participation in Virtual Power Plants (VPPs) which support the grid.

VPPs can include a network of wind farms, solar arrays, combined heat and power units, but in the context of this report they are clusters of solar arrays and/or DLiBESS remotely managed and operated with the intention of supporting the grid, e.g. by frequency stabilisation, but also with the intention of providing some return to homeowners, who are known as prosumers: producers and consumers of electricity. VPPs are typically cloud-based platforms and the DLiBESS are fully automated. Consumption of electricity by the prosumer and generation by the grid are monitored in real time in order to facilitate the operator to offer the best value electricity to its customers. When demand by the grid is less than production, energy is stored in the VPP and is available in seconds to provide grid support and enable smart energy management. The latter is the ability to, for example, utilise rapid response, distributed energy generation and storage systems to deal with uncertainty and rapidly changing demand. One VPP operator stated that 70% of revenue and savings were provided to prosumers, representing 20% more than if the prosumers were benefitting from TOU billing alone.

An extreme example of the emerging VPP market is the "Rent a Roof" concept [31] where a company pays for the installation of a PV+DLiBESS system and the feed-in tariff is assigned to the company. Some return is provided to the homeowner, but otherwise the latter has no significant engagement with, nor have any knowledge of, the DLiBESS.

Finally, one possible driver not linked to economic considerations is protection against power outages. Such events are relatively rare in the UK: however, Tesla introduced the Powerwall DLiBESS following outages in California to allow both home usage and EV charging when the domestic electricity supply fails [32].

3.2 Environmental and economic drivers for second-life LiBs

By the early 2030s, there could be 20 million EVs on European roads and more than 100M by 2040 [33], with an estimated 112 – 1000 GWh of second-life EV LiBs available by 2030 [34-36] as the first significant wave of end-of-first-life (EoFL) battery packs occurs. In response to this challenge, China, South Korea and Japan are developing robust recycling (i.e. materials recovery) and second-life infrastructures [37]. However, there is only a limited LiB recycling industry in the UK at the present time [38] yet it is estimated that there will be 75,000 to 105,000 EoFL EV lithium-ion batteries in the UK by 2025 [39] and these represent potential environmental and safety risks and hazards [6]. However, there are UK companies poised to take up the recycling/repurposing challenge [40-42].

The extraction of the metals required by LiBs is material-rich and costly, and labour, time and carbon-intensive. Thus, 1 ton of lithium ions requires 250 tons of the Li-rich mineral ore Spodumene or 750 tons of Li-rich brine [43]: in addition, each ton of lithium requires 1900 tons of water [44] and each kWh of LiB produced requires 50 – 65 kWh of electricity and generates 55 kg CO_2 if the electricity comes from a coal-fired power station [45].

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[3] This was partly responsible for one major DLiBESS manufacturer pulling out of the UK DLiBESS market.

Needless to say, the extraction and processing of metals is also harmful to the environment [6, 46] . On the other hand, reuse, remanufacture or repurposing could extend battery life by 7 – 10 years [47-49] thus contributing to waste minimisation, delaying or reducing materials recovery (which is currently energy intensive [6]) and reducing gross energy demand and Global Warming Potential by 15 – 70% [50] by reducing greenhouse gas emissions [51]. The World Economic Forum Battery Alliance estimates that moving from the current linear economy in EV LiBs to a circular economy could reduce global CO_2 emissions by 35Mt with an attendant economic gain of $35bn. With respect to the latter, reusing or repurposing EV LiBs, for example, could lower the cost of the EV charging infrastructure by 90% by 2030 [52].

However, it may be that the global uptake of LiBs places major pressure on the supply of essential material, hence driving recycling (materials recovery) over re-use, remanufacture or repurposing. Thus, it has been estimated that, by 2030, materials recovery from end-of-life LiBs could produce approximately 10% of Europe's cobalt consumption by the automotive sector [39].

3.3 The availability of second-life LiBs

The EoFL of an EV battery pack is generally taken as 75 – 80% State-of-Health (SoH, one definition being the ratio of the current charge when fully charged to the initial, rated full charge, expressed as percent [53][4]). Apart from recycling, EoFL EV battery packs can be reintroduced into the supply chain as follows:

- **Reuse** is defined as using all or part (i.e. modules) of a battery for the same application as its first life (see Figure 3).

- **Remanufacturing** involves replacing multiple defective modules and reusing the pack in its original application.

- **Repurposing** is the disassembly of the original pack, assessment and replacement of modules and assembly into a battery for use in a different application to the original pack [54]. At the present time, the most likely destination for repurposed batteries is in stationary energy storage.

End-of-Second-Life (EoSL) is generally stated as 50-60% SoH (with respect to rated SoC at Beginning-of-Life, BoL) and is limited by concerns over very significant degradation at lower SoH and the attendant safety implications including spalling of the electrodes, lithium metal plating and dendrite formation [54-57].

The current assumption that all second-life LiBs come from end-of-life EVs is incorrect. There are three common routes to market for these batteries [58]:

1. The battery pack is replaced on warranty,

2. An EV is an insurance write-off and the Authorised Treatment Facility (ATF) dealing with the scrapping of the EV sells the battery and

3. A pack is upgraded [58].

At the time of writing most second-life LiBs in large and mid-sized SLLiBESS come from (1) and (3) [59] . An important aspect of the write-off of EVs or warranty replacement of EV battery packs, raised by an EV OEM, was the loss of the connection between the Vehicle Identification Number (VIN) and the serial numbers on modules in packs. As a result, all the information stored in the battery management system (BMS) essential to ascertain if the modules were fit for use in second-life applications is lost. This loss of connection between pack and vehicle was also reported by a second EV OEM that repurposes packs

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[4] This figure is increasingly being questioned as it was formulated by the US Advanced Battery Consortium in 1996 (J. Zhu et al., Cell Reports Phys. Sci., 2 (2021) 100537. https://doi.org/10.1016/j.xcrp.2021.100537.) prior to the emergence of LiBs.

from EV vehicles in the company's own prototype testing fleet for use in industrial scale LiBESS[5]. Both these EV OEMs, and manufacturers repurposing batteries for storage which were consulted as part of this research, expressed strong faith in the safety and durability of their second life batteries based on a significant body of statistical data on first and second-life failures rates as well as customer satisfaction.

Figure 3 Reuse, remanufacturing and repurposing
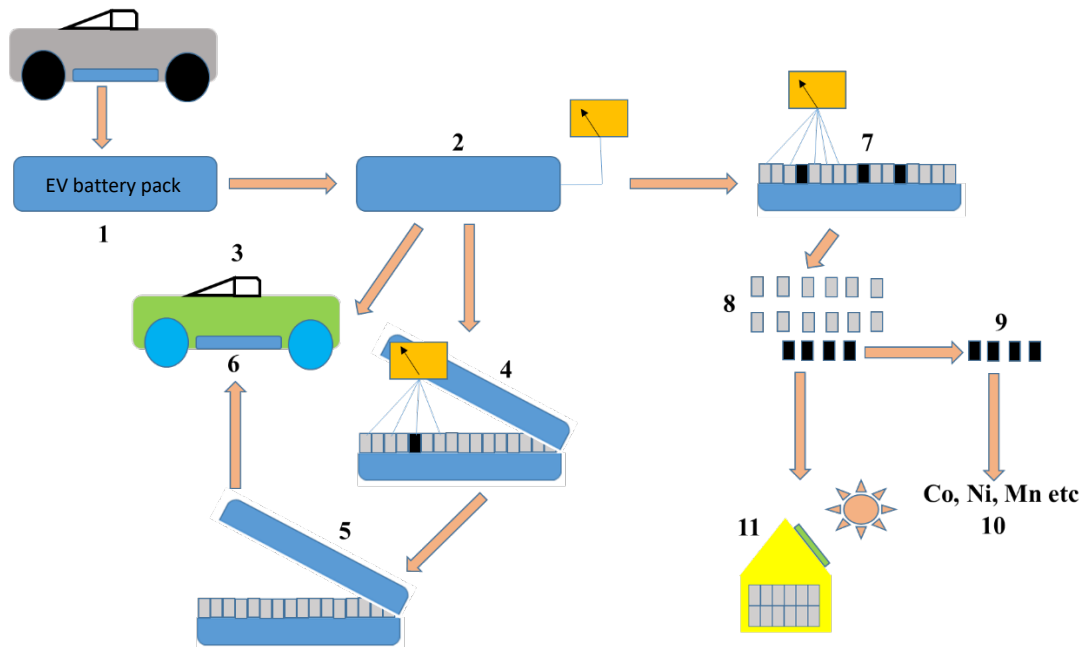
(1) EV to be scrapped and battery pack removed. (2) Gateway testing on the pack, if the pack passes the testing criteria it is (3) reused in a second EV. If the pack does not pass it is (4) opened, modules tested individually, defective modules replaced and the modules rebalanced (5). The remanufactured pack is then used in a second EV (6). (7) If multiple modules are defective the pack is opened and (8) the modules tested. Defective modules are (9) separated and (10) sent for materials recovery. (11) The remaining modules are repurposed into a LiBESS.

With respect to the future, scrapped EVs are set to be a significant source of second-life LiBs as the current EVs reach EoFL, or are scrapped after being sold on as a used vehicle. Scrappage will also increase as owners upgrade to new, more efficient EVs with greater functionality and longer range, and as a result of the drive by the UK Government to replace new diesel and petrol cars by EVs in 2030. Thus, the International Renewable Energy Agency (IRENA) estimates that the 6M EVs globally on the roads in 2019 must increase to 745M by 2040 if the requirements of the Paris Climate Agreement are to be met [60].

In general, car scrappage, as well as driven by economic and legislative factors, is also a function of the total number of cars on the road (known as the "parc") and the rate of new car sales. By taking such factors into account, Skeete and co-workers [39] estimate a stockpile of ca. 75,000 to 105,000 EoFL EV batteries in the UK by 2025. This should be considered in the light of the following:

1. Globally, ATFs are not yet ready to process such volumes of large LiBs primarily because the commercial imperative is not yet clear, the development of the necessary technology is still very much in its infancy and there is a plethora of cell form factors and pack topologies, all of which present their own challenges [6].

2. According to experts consulted as part of this study, there is currently only a very limited EV battery service, maintenance and repair infrastructure in the UK, this is

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[5] In addition to the important implications of the loss first life history for second-life applications of LiBs, when an EV is sent to an ATF, the original EV OEM has no way of ascertaining the fate of the EV pack, but retains extended producer responsibility for that pack[59].

due to two factors: firstly, the current very low volumes of batteries requiring repair does not justify the cost of training, and second due to the extreme caution of OEMs to give access to the BMS data of EV battery packs. However, it does not seem unreasonable to expect this to grow.

3. The falling cost of new LiBs. Prices have fallen by ca. 90% since 2010, such that the average price for a new LiB across all markets was ca. $137 per kWh in the first quarter of 2021 [58, 61], and EV OEMs predict price parity with diesel and petrol cars in 2024 [37]. As a result, the economic incentive for reuse and repurposing of LiBs is less attractive [61]: however, fluctuations in the price of, for example, lithium carbonate and Spodumene could have a major influence on this.

4. Leading research from Mckinsey and Co. [62] suggests that there will be between 112 -227 GWh of second-life LiBs available per year by 2030, whereas the demand for industrial LiBESS is expected to be 183 GWh. Therefore, it could be that 60-100% of the demand for industrial LiBESS could be satisfied by second-life EV LiBs [21, 63]. However, as the uptake of EVs increases it is predicted that global LiB demand could reach 2000 - 3900 GWh y^{-1} by 2030 [62, 64, 65], with a comparable number of EV batteries, which make up the majority of these, reaching EoFL 8 - 10 years later. This may then exceed global industrial LiBESS demand with a total of 2850 GWh having been deployed by 2040 according to BloombergNEF forecasts[66].

On one hand the projected surplus of second-life batteries is good news for the DLiBESS industry. However, if the surplus second-life LiBs are not to be utilised, then the UK Waste Batteries and Accumulators Regulations 2009 [67] prohibits the disposal of EoL LiBs in landfill, and hence there will have to be significant innovation and investment in materials recovery if the consequences of illegal dumping of LiBs is to be avoided [68]. Experience of lead acid battery recycling dictates that recycling is driven by regulation. To this end, the EU Batteries Regulation (discussed in detail in section 8.6) seeks to increase the recovery of key metals including lithium, nickel and cobalt from scrapped LiBs. The current requirement is 50% by mass, and the draft regulation requires this to increase to 85%. In addition, LiB OEMs will be required to incorporate minimum levels of these recyclates into new LiBs. In the view of a major EV battery research organisation, whilst likely to drive the much-needed innovation, there is also the danger that it will drive materials recovery at the expense of second-life.

3.4 Factors determining the price of second-life LiBs

In the view of a major EV battery research organisation, the economics of second-life are on a knife-edge due, amongst other factors, to the fact that the disassembly, assessment and sorting of modules and packs is labour intensive and costly. This is caused by the lack of standardisation among EV OEMs, for example the use of different cell form factors and glue which prevents automation and requires manual disassembly: the latter can require two operatives and 8 – 16 hours per pack [69]. It has been predicted that there will be 250 new EV models from more than 15 EV OEMs by 2025 [21]. Currently, the cost of disassembling a pack to module level has been estimated as $71/kWh with an additional $16/kWh to disassemble to cell level, i.e. a total cost comparable to the price of new LiBs [21].

A second major factor is the relative price of new LiBs and, as stated in the previous section, this has fallen very significantly over recent years. Unfortunately, estimates of prices of second-life batteries are subject to very wide variation (for a review of this, see research from M. H. S. M. Haram et al.[70]): e.g. £32/kWh[6] to £218/kWh [63, 71, 72]. It has been reported that using second-life LiBs in DLiBESS would become profitable at

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[6] Rates: £1 = $0.73 and €0.84.

£32.3/kWh [73], but this has also been questioned as too optimistic [74] and it has been predicted that new LiBs become more profitable than second-life LiBs if the price of the latter rises from the break-even point of 60% of the cost of new batteries to 80% [75].

Overall, attempting to predict the future market for second-life LiBs, and hence for SLDLiBESS, is extremely challenging due to the lack of data and information: in addition, the market will be driven to a large extent by the pace of regulatory intervention which is extremely challenging to predict.

4 Summary of the general hazards associated with LiBESS

While the inherent risks may be different for second-life compared with new LiBs, the type of hazards remain the same. This section therefore provides an overview of the general hazards associated with LiBESS to establish a baseline of understanding, before discussing the particular risks of second-life LiBs in Section 5.

4.1 Electrical hazards

Batteries cannot be shut down and hence accidental contact with both poles of a charged EV battery (ca. 300 – 600V [76]) can lead to electric shock or electrocution. If LiBESS are installed by accredited engineers, any such risks will be low. However, incorrectly installed systems (for example incorrectly gauged wiring) could result in failures leading to partial discharge or arcing, which are potential ignition sources.

4.2 Electrolyte spillage

The electrolyte in new lithium-ion cells contains a mixture of organic cyclic and linear carbonates, the $LiPF_6$ and up to 5% by volume additives. $LiPF_6$ is harmful if swallowed, toxic in contact with skin and causes severe skin burns and eye damage: in contrast, the organic carbonates comprising the solvent are generally regarded as having about the same toxicity as ethanol. The additives are commercial secrets but include some extremely toxic chemicals [77]. It is generally accepted that calendar and cycling ageing of LiBs leads to gas evolution (or so-called 'gassing'), producing solids, liquids and gases [78]. There is insufficient analytical data in the public domain to make definitive statements of the products from gassing, but alkanes, alkenes, CO_2, CO and HF have all been detected [79-83] as well as alkylfluorophosphates [84]: the latter posing a significant chemical hazard. Thus, contact with the electrolyte from a second-life battery could represent a greater hazard in terms of toxicity than from a new LiB. However, LiBs are sealed and therefore the chances of accidental skin contact with electrolyte from a SLDLiBESS must be considered to be slight and the associated risk low.

4.3 Thermal runaway

LiBs are the first batteries to employ an organic solvent in the electrolyte (typically a mixture of ethylene carbonate and other cyclic or linear organic carbonates [85]) rather than water, as the very high cell voltages available (currently up to 4.2V) would result in the electrolysis of an aqueous electrolyte and the production of hydrogen and oxygen. The combination of flammable organic electrolyte with high energy density (as with diesel or petrol) can lead to fire or even explosion if the energy is released in an uncontrolled manner, e.g. by abuse.

4.3.1 Forms of abuse

Lithium-ion cells are regarded as stable unless abused: such abuse is generally caused by heating, metal penetration, blunt trauma (crushing) or overcharging [86]. With respect to DLiBESS, the most likely abuse is heating (e.g. poor ventilation: this is believed to be one of the causes of the LiBESS fire in Arizona in 2012 [87, 88]) or overcharging due to, for example, failure of the BMS. Additional factors compromising SLDLiBESS could be poor selection of cells or modules such that one or more cells have passed the "knee" in terms of ageing, after which ageing accelerates (see section 5), cells with mismatched SoH and/or an inappropriate BMS (for example, in a DIY SLDLiBESS).

To demonstrate the potential impact of physical abuse, Figure 4 shows stills from a video taken from an experiment conducted by the Commonwealth Scientific and Industrial Research Organisation[7] (CSIRO) in 2019 simulating the reversing of a vehicle with towbar into a DLiBESS at 100% SoC at 10 km h^{-1}. As can be seen from the figure, the penetration of the DLiBESS results initially in black "smoke" (see fig. 4(b), probably the release of toxic metal oxide nanoparticles from the cathode [89]) followed by the white vapour, fig. 4(c). There is a small glow in the lower right quadrant of fig. 4(c) that may be the ignition source for the subsequent explosion in fig. 4(d), c.a. 20 seconds after impact.

Figure 4 Stills taken from an experiment conducted by CSIRO simulating the reversing of a vehicle with a towbar into a DLiBESS at 10 kmh^{-1}.

(a)

(b)

(c)

(d)
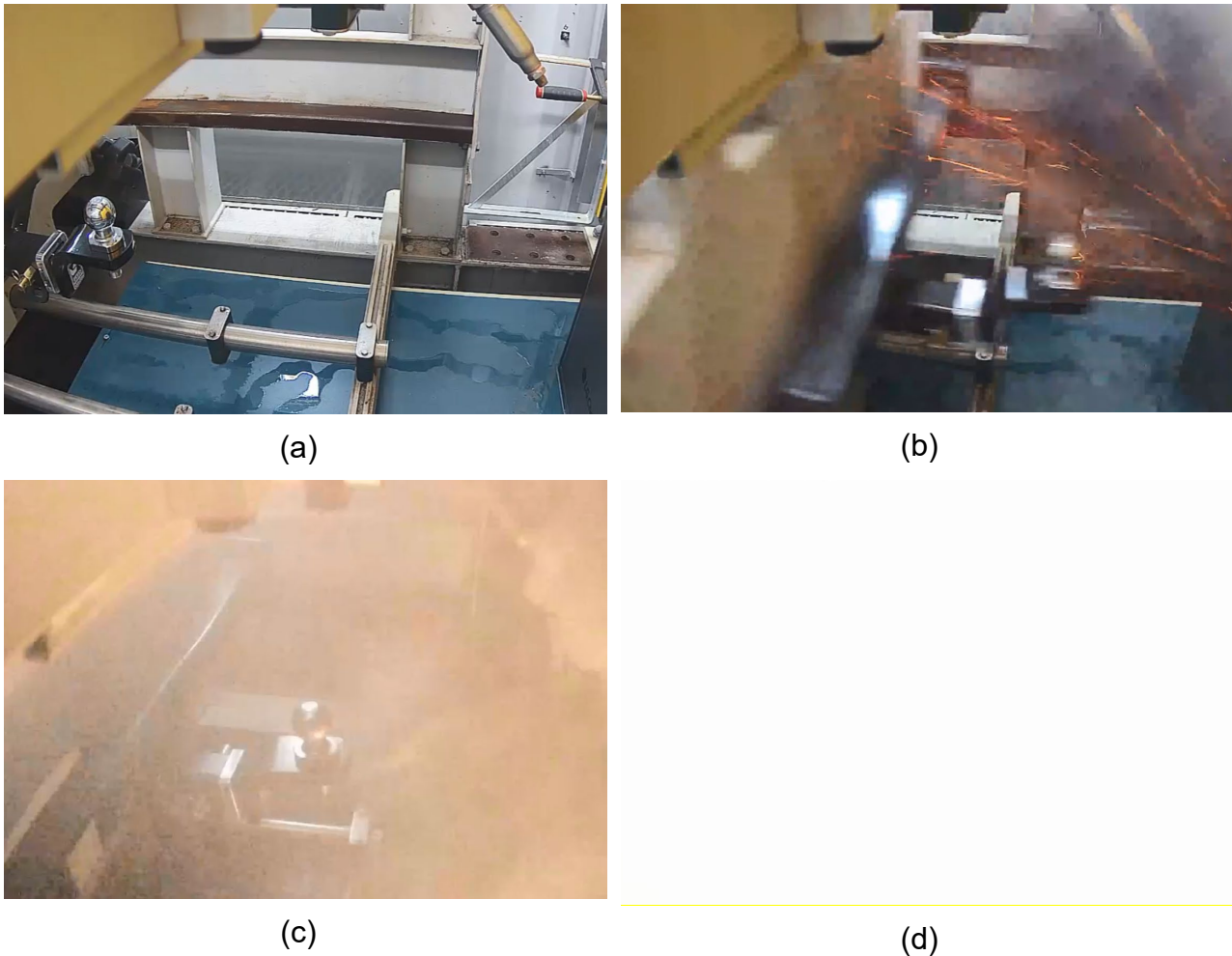
(a) 2 seconds from the start of the test, before impact; (b) a few seconds after the moment of impact, (c) 13 s after impact and (d) vapour cloud explosion.

4.3.2 Spontaneous failure

Spontaneous ignition of LiBs can also occur, as seen with electric vehicles [90], the cause of which is uncertain [86], and generally postulated as due to defects or contamination introduced during manufacturing [78, 91]. The probability of these defects occurring is often given as 1 in a million to 1 in 40 million [79-81] nevertheless, such defects were responsible for a general UK recall of LG Energy Solutions residential units manufactured between April 2017 and September 2019 in May 2021: this followed similar recalls in Australia in March 2021 and the USA. The recalls followed reports of the units overheating which was ascribed to problems with the electrode manufacturing process by the company

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[7] CSIRO is an Australian Government agency responsible for scientific research. The test was conducted on 13 November 2019 using a 6.4kWh NMC battery. The test was intended to inform the AS 5139 standard "Electrical installations —Safety of battery systems for use with power conversion equipment". The towbar was driven at 10 km/h.

[92]. Thus: (1) even the most highly experienced manufacturers may inadvertently allow defective cells to be placed on the market and (2) there is much uncertainty around the statistics.

4.3.3 The events during thermal runaway

In broad terms, thermal runaway can be described as uncontrolled positive feedback. However, the precise definition of thermal runaway remains a matter for discussion: thus, some authors define it as the point at which a fixed rate of temperature increase is surpassed, e.g. 1°C min^{-1} [93] or 10°C s^{-1} [94], whereas a more accurate (but less easy to measure) definition is that of a self-sustaining heating process, i.e. once the temperature of a cell passes a point of no return, the exothermic reactions continue to generate heat and the cell will progress inevitably to an exponential increase in temperature [95].

The events leading up to and including thermal runaway are also still a matter for research. Taking abuse by heating as a starting point: the first stage is generally accepted to be the breakdown of the Solid Electrolyte Interface or SEI, a protective layer that forms on the graphite anode particles during the first charge. This layer prevents further contact between the anode and solvent, but allows free passage of lithium ions. The breakdown of the SEI is stated as commencing around 90°C [78, 89, 96] or as low as c.a. 60°C [97]. The onset is dependent on the degree of lithiation of the anode: this process is exothermic and has been associated with the onset of self-heating [98]. The breakdown of the SEI results in the production of small chain alkanes, CO_2 and oxygen [78]. In general, it is accepted that the SEI can self-heal up to ca., 80 – 120°C [91, 97] forming a "secondary SEI" [96] that is less compact than the initially-formed layer and hence may allow exothermic reactions with the organic solvent of the electrolyte, again generating small chain alkanes and heat, and CO. In addition, hydrogen gas is produced from the reduction of the binders employed in the anode (e.g. polyvinylidene fluoride or polyvinylidene difluoride, PVDF [78]).

Between ca. 120°C and 240°C internal short circuit and the accompanying catastrophic release of heat can take place depending upon the composition of the separator. As was stated in Section 2.3, typical separators are made of polyethylene, polypropylene or a mixture of polymers, the latter may be coated with a ceramic layer. Thus, the melting point of polyethylene is 130°C, polypropylene 170°C and ceramic-coated polymer/mixed polymer separators c.a. 200°C [78, 91]. The collapse of the separator was previously believed to be the trigger for thermal runaway: however, at temperatures above 150°C exothermic collapse of the cathode structure takes place to generate oxygen and, in some cases, highly oxidising oxides: the onset temperature of this process depends upon composition, e.g. from 150°C for NMC cathodes to c.a. 310°C for LFP [89, 91, 94] cathodes. The oxygen produced can cross over to the anode where it is consumed in a highly exothermic reaction, sufficiently exothermic to initiate thermal runaway at temperatures significantly less than that needed for separator collapse [98]. LiBs having LFP cathodes are generally considered to be more stable due to the higher onset temperature for the collapse of the cathode structure [80]: however, this may simply delay ignition and hence facilitate explosion. With respect to this, it is worth noting that the explosions of the LiBESS in Brisbane [99] and Beijing [100] both employed LFP cells.

As the temperature of a cell rises, the solvents comprising the electrolyte will vapourise, e.g. the boiling point of dimethyl carbonate (DMC) is 91°C and that of ethylene carbonate (EC) is 248°C [101], and eventually vent as a result of burst caps activating (in cylindrical and prismatic cells) or a pouch cell rupturing. It is not unreasonable to assume that such an event would terminate thermal runaway [102]: however, Feng and co-workers [91, 97, 103] have shown that lithiated graphite and NMC cathode powders undergo direct, solid-state electrochemical reaction at temperatures ≥ c.a. 250°C that is highly exothermic and generates sufficient heat to raise the temperature of the cell up to 800°C and perpetuate thermal runaway.

The mechanism of thermal runaway initiated by overcharge involves the same stages as described above but commences with the over-lithiation of the graphite anode, causing lithium metal to deposit on the surface [104]. The accompanying over-delithiation of the cathode and the collapse of its structure increases the cell resistance and causes Joule heating. The metallic lithium reacts exothermically with the solvent in essentially the same way as the lithiated graphite anode and can form dendrites that grow through the separator [105, 106] to the cathode and cause an internal short circuit with attendant and very significant Joule heating. However, it has been suggested that most dendrites will melt due to the very high current density being passed and the attendant Joule heating [107].

4.3.4 Gases vented during thermal runaway

The exothermic reactions following abuse generate a mixture of gases that includes on venting: H_2 (up to 45% [108]), SO_2, NO_2, HF, HCl, HCN, CO, CO_2, droplets of organic solvent and a range of small chain alkanes and alkenes, in other words, a vapour cloud. It appears that, in general terms, the composition of this vapour cloud does not vary with chemistry, form factor or manufacturer [104]. The vapour has been routinely confused with smoke [81, 109], but is actually the pre-ignition phase: there is insufficient oxygen inside cells undergoing exothermic reactions to sustain ignition [91], but the vapour may ignite immediately on venting, in which flare-like flames can be produced. If the vapour does not ignite immediately, due to low SoC or insufficient oxygen, then a vapour cloud explosion could result ([86] and references therein). The hazardous chemicals alkylfluorophosphates have also been detected, but such studies are limited and the implications of the emission of these species yet to be researched in detail [110]. Further details on the toxic gases released can be found in BEIS *"Domestic battery energy storage systems: a review of safety risks"* [1].

Once a cell has passed the point of no return, it is critical to prevent this cascading to adjacent cells which can be challenging. However, codes and standards require design for safety, which includes preventing propagation, see section 8.

The first confirmed vapour cloud explosion caused by LiBs in thermal runaway occurred on 19 April 2019 and involved the 2MWh LiBESS in Surprise, Arizona, see Appendix 1 for a case study. It is suspected that thermal runaway was triggered in two cells in a module in one of the racks by an electrical arc, and propagated to all the remaining modules in the rack. The modules went into thermal runaway without ignition and produced copious amounts of white vapour. One of the reports on the incident, quoting a fire officer who was first on the scene, draws attention to the production of a heavier-than-air white cloud. The DNV GL report quotes its expert as stating that "the composition of gases is constant across all form factors, chemistries and manufacturers" [105] – an extremely important statement if correct. The literature is certainly full of reports of white vapour or "smoke" being produced from cells with a range of chemistries as a result of thermal runaway. Research conducted by Newcastle University as part of the ReLiB project [111] and the literature has shown that if LiBs are abused at ≤ 50% SoC the white vapour does not necessarily ignite [112]. As stated in section 7.3.3, in addition to HF, HCl, HCN, hydrocarbon gases, CO, H_2 [78, 105, 113] it is well-established that the vapour also contains droplets of the organic carbonates employed in the cell electrolyte [78]. Figure 5(a) – (f) below show stills from a video taken during one of the Newcastle University joint ReLiB [111] and SafeBatt [114] experiments at the DNV site at RAF Spadeadam in April 2021 in which a single 1.67kWh EV module was penetrated by a nail at 40% SoC. As was observed in previous experiments involving nail penetration at SoC ≤ 50% [86] a dense, white vapour was produced: in fact two types of vapour can clearly be seen, one buoyant and one heavier than air: it is not clear what determines the relative amounts of these gases, but it may be a function of the cathode chemistry and the temperature of the cell or module. HF concentrations up to 120 ppm and hydrogen & CO concentrations up to 2000

ppm were recorded in the container. The lower explosion limit for the white vapour is c.a. 6 - 12% [108].

Figure 5 Stills from the video taken during one of the Newcastle University joint ReLiB and SafeBatt [114] experiments at the DNV site at RAF Spadeadam in April 2021

(a)	*(b)*	*(c)*
(d)	*(e)*	*(f)*
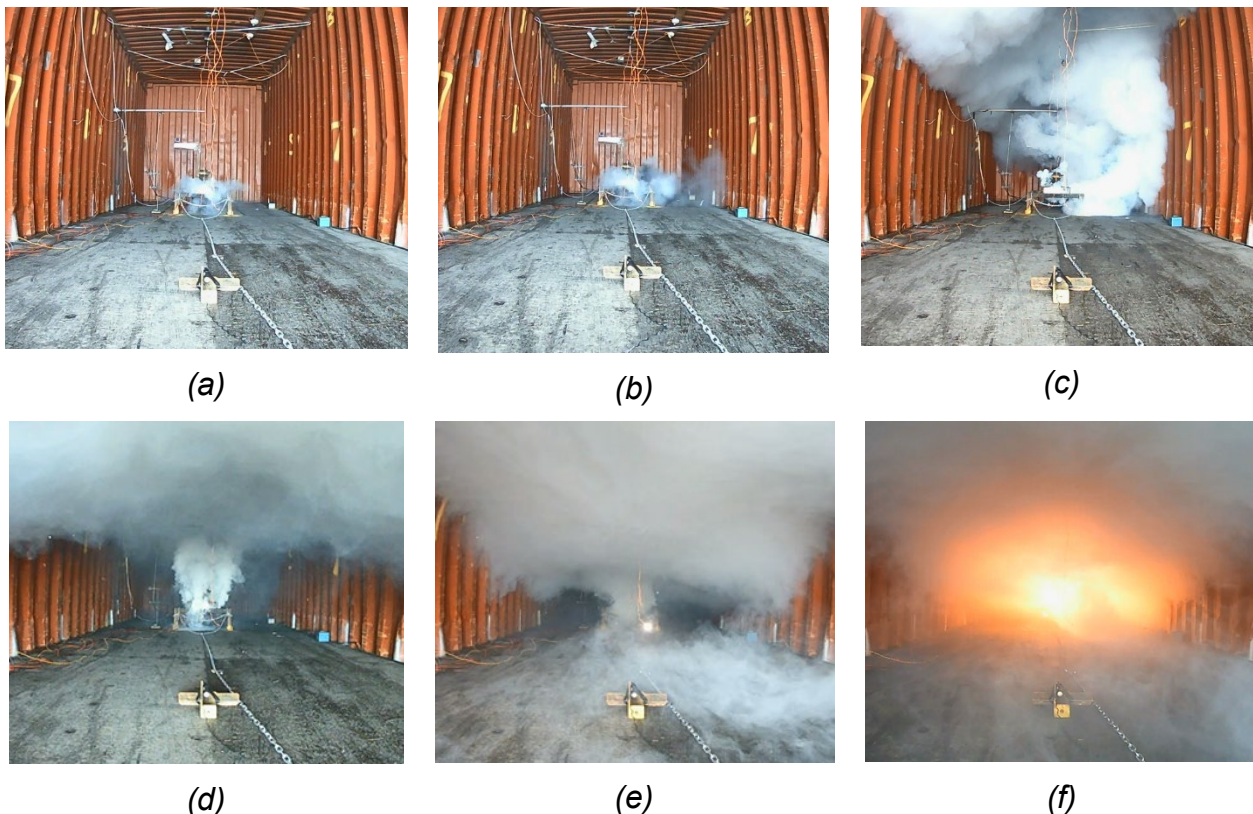
A single 1.67kWh EV module was penetrated by a nail at 40% SoC. (a) Nail penetration, (b) less than one second later pouch cell(s) burst ejecting black cathode particles, (c) 17 s after penetration, (d) 56 s and (e) 79 s after penetration and evolution of second, heavier than air vapour, and (f) 87 s after penetration and module self-ignites, consuming vapour cloud and drawing it back. The experiment was conducted in a standard 76.8 m^3 sea container.

It should be noted that the experiment depicted in fig. 5 was part of a project aimed at researching the relative effects of immediate vs delayed ignition of the white vapour cloud, as well as facilitating the education and training of first responders. Hence the module employed was not protected by a BMS and it was subjected to abuse significantly above industry norms in order to ensure that the cells were driven into thermal runaway.

The module in figures 5(a) - (f) contained 8 x 53Ah NMC pouch cells: the 14 LG Chem modules in the LiBESS in Surprise, Arizona that first went into thermal runaway each contained 28 x 64Ah pouch cells, a 55-fold difference. Further, the contention of the DNV GL report [105] is that the release of the Novac 1230 suppressant prevented ignition of the gases produced by the cells in thermal runaway by displacing air from the container, and so allowed the gases to build up to dangerous levels.

The cells in the Arizona LiBESS were initially all at > 90% SoC but the vapour did not ignite due to the displacement of the air from the container by the suppressant [105]. Hence if LiBs of any cathode chemistry, form factor or manufacturer are abused at a low SoC and/or the concentration of oxygen is reduced below that necessary for ignition in some way (irrespective of the form of abuse), the toxic white vapour so produced can build up and hence there could be a possibility of a flash fire, fire balls developing, or in extreme cases even a vapour cloud explosion [86]. This explosion hazard, along with the toxicity of the white vapour, could be faced by the occupiers and first responders called to a fire in a home containing a DLiBESS or SLDLiBESS.

5 The risks and hazards specific to second-life LiBs

The thermal stability of LiBs is generally assessed on the basis of: the onset temperatures for exothermic reaction, self-heating and thermal runaway, as well as the time taken to reach thermal runaway, maximum temperature and the activation energy for thermal runaway [115-119].

The hazards associated with second-life LiBs are broadly the same as for new LiBs, i.e. toxic gas [1], fire and explosion. However, the literature on the effect of ageing on the thermal stability of LiBs is limited and largely focussed at the cell level. Most such papers concern 18650 cells, presumably for reasons of cost: studies on larger cells or modules are rare and studies on the ageing of cells from actual EV packs extremely so, see for example [120-122]. Given that heat is dissipated through the surfaces of a LiB, but is generated throughout its volume, the extrapolation of data obtained from cells to predict the thermal behaviour of modules or EV battery packs should be considered with caution.

In addition, the response of cells to abuse is highly dependent upon the conditions [102] and hence the same cells in different test facilities may vary in their responses. Finally, the definition of thermal runaway in terms of a measurable temperature rise is highly subjective [86]. As a result of all such factors, it is currently challenging to predict the impact of ageing on the thermal stability of EV battery packs, or the intensity or magnitude of the fires and explosions arising from thermal runaway. To do so will require a significant body of further work including studies on the effect of cycling as a function of temperature, cell form factor, chemistry and capacity as well as calendar ageing[8] as a function of these parameters and SoC, on the thermal stability of cells, modules and packs.

The following sections are an assessment of the literature to date which often highlights the need for further understanding of the long-term performance of second-life LiBs [123].

5.1 The effect of ageing and unknown stress and/or abuse

It is generally accepted that the capacity loss with use (cycling) in first life in an EV is essentially linear, although the rate of ageing has been shown to depend upon cell chemistry: for example, LFP cells degrade slowly even up to 50% SoH [83] whereas NMC cells deteriorate rapidly after 70-80% SoH [124]. At some point, however, there is a change in and/or an additional ageing mechanism which leads to an increased ageing rate. The time at which this occurs is referred to as the "knee", the battery has reached its final end-of-life [83, 125] (see Figure 6) and should be immediately retired from operation for safety reasons [123].

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[8] Calendar ageing simply refers to the changes in the cells of a LiB when in the charged but passive state, i.e. not charging or discharging.

Figure 6 Representation of the "knee": the time at which ageing accelerates and lithium-ion batteries reach final EoL
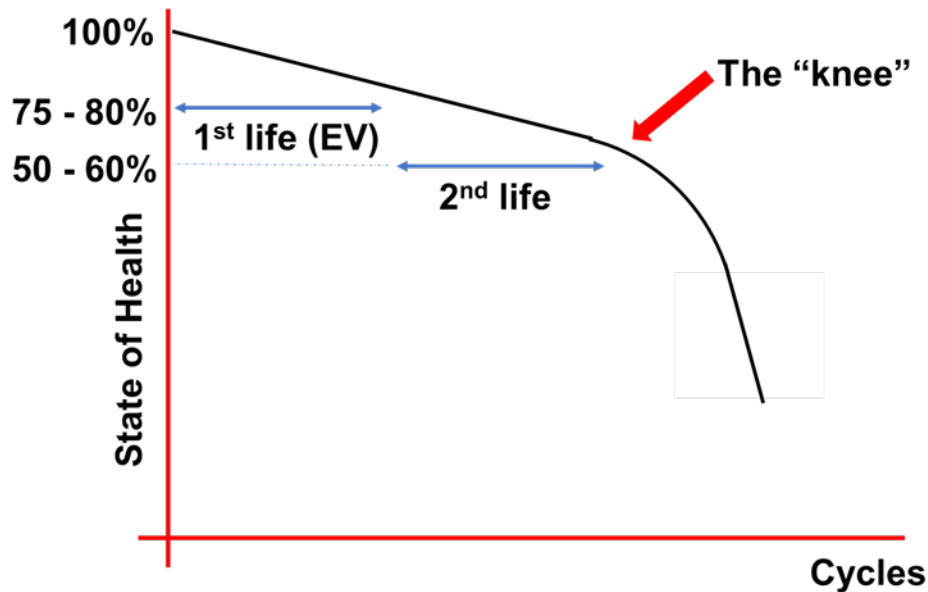
Lithium-ion cells may pass the knee during their first life: if NMC cells do so, there is no slowdown in ageing, even in less demanding applications [83, 125]. Under normal circumstances the final EoL is taken as 50 – 60% SoH [54], after which severe and potentially dangerous deterioration is expected to occur; however, there is an indication that even at 70% SoH, serious structural damage may have already occurred on the cathode that can lead to accelerated ageing [117, 126].

While it is generally considered difficult to predict the point at which the knee occurs, recent developments mean that it may be possible and has been achieved using capacity degradation and machine learning [127], and capacity fade data along with nonlinear autoregressive network modelling [128], albeit these methods are not currently chemistry agnostic.

Research suggests that second-life LiBs will also have greater cell-to-cell variability than new batteries and that this will increase with ageing [123]. Additionally, the SoH of modules recovered from EV battery packs may vary according to location in the pack (see Figure 10) [120], and this can result in accelerated ageing [83, 117, 126].

5.1.1 Calendar ageing and cycling at normal currents

It is generally accepted that calendar ageing, and cycling under the conditions and between the potential limits set by the manufacturer, simply reduces the lithium inventory in cells as a result of the reduction of electrolyte, thickening of the SEI and attendant trapping and isolation of lithium cations in the SEI [120].This does not reduce the thermal stability of the LiB [89][96] and may even improve stability slightly, as the lithium cations are then unable to participate in the reduction of the solvent at the lithiated anode particles when the SEI breaks down [97][118].

However, calendar ageing and the normal operation of an EV pack within the limits specified by the manufacturer could also decrease stability. During ageing, other structural changes take place which affect the degradation process. With a decrease of SoH, there is higher inhomogeneity of lithium in the anode and a reduction of the graphitization of the anode. This leads to the fragmentation of the anode which can lead to increasing resistance and Joule heating. The cathode itself does not change much during benign ageing, however the mixed metal oxide gradually spalls and may finally fall off [129]. Therefore, it is believed the greatest impact on battery safety is by the anode. There is also a decrease in the separator pores that increases the internal resistance [130, 131].

Additionally, dry spots in cells, where the electrolyte has been consumed during use, can result in Joule heating [93][132].

5.1.2 Cycling at low temperatures and/or high C-rates

In contrast, any process that removes lithium inventory as lithium metal, such as cycling at low temperatures or high C-rates, can have a marked and detrimental effect upon thermal stability [96, 115, 118, 121, 128]. In these scenarios, the lithium metal reacts exothermically with the electrolyte producing gaseous products and the deposition of solids from the electrolyte on the anode also takes place, as well as the precipitation of solvent fragments in the electrolyte which could block the pores of the separator [129].

As a result of these processes, there is an increase in internal resistance and the formation of non-electrochemically active lithium dendrites: these thin tendrils of lithium metal are formed when significant lithium metal plating occurs [125, 130]. The dendrites reduce the temperature of the self-sustaining exothermic processes (from 80°C to about 50°C) and the temperature of thermal runaway from 170°C to about 100°C. Therefore, there is a much shorter time needed for the battery to reach thermal runaway [89, 125] and the lithium metal dendrites can penetrate the separator and cause catastrophic internal short circuit. Currently, methods to detect lithium metal plating in first life are still at the experimental stage [106].

5.1.3 Loss of lithium inventory during ageing

Lithium metal plating occurs during charging when the flux of lithium ions to the anode is, for any reason, insufficient to match the charging current, and those lithium ions at the anode are then reduced to the metal. A number of factors can cause lithium metal plating: the low solvent viscosity and low ion diffusion coefficients at low temperatures will demand low charging C-rates, and even at ambient temperatures, high charging currents can cause plating if the flux of lithium ions is insufficient.

A natural extension of this theory concerns operation under normal conditions: thus, normal operation under the conditions specified by the LiB manufacturer continually removes the lithium inventory as benign lithium ions. However, at some point, it is not unreasonable to postulate that the concentration of the remaining lithium ions in the electrolyte will be insufficient to provide sufficient ion flux during charging even under normal C-rates, and lithium metal plating will occur. It could be that this is the point at which the knee occurs, though further research is needed to support this theory.

Thus, in their study of Nissan Leaf modules taken out of the vehicle at EoFL at 62.8 – 71.2% SoH and prior to the knee, Braco and co-workers [122] employed accelerated ageing on 6 modules within the potential limits specified by Nissan, which caused 5 of the 6 modules to pass the knee. The accelerated ageing associated with the knee was specifically attributed to lithium metal plating by the authors.

5.1.4 Concluding remarks

A simple example can highlight the extremes of ageing of LiBs that are likely to be seen in practice during first life: private EVs will be charged at most once per day and probably at low C-rates overnight, whilst taxis are charged far more often, and generally using fast charging, both of which may accelerate ageing, the possibility of lithium metal plating and hence thermal instability [129].

Additionally, battery packs may have suffered physical abuse (see Section 4.3.1) during first life (e. g. via a road traffic collision) and/or disassembly, and this can result in cells being crushed or coolant leakage (larger energy density EV packs in particular require active cooling, usually using liquid cooling loops [133]), either of which can lead to thermal runaway and fire [121].

However, there is a need for more research to gain a clearer understanding of the effect of ageing on thermal stability, particularly with respect to cell chemistry. This is highlighted in the study by Wang and co-workers[121] who tested both new and aged batteries. To begin with, they cycled 14 Ah LFP pouch cells after calendar ageing for 10 years (84% SoH at start of tests). The cells were cycled at -10, 0 and 25˚C: capacity loss, lithium metal plating and dendrite formation were observed in the cells cycled at -10˚C and at C-rates ≥ 0.2. In contrast, fresh 19Ah LFP pouch cells from the same manufacturer showed little or no capacity loss after cycling at 1C and 25˚C for 10 weeks, followed by 50 weeks cycling at 1C and -10˚C then 10 weeks cycling at 25˚C again. The SoH dropped to 70% after the cycling at -10C, but recovered to 98% after the second cycling at 25˚C. This indicates that the age of the cell can also have an impact on the effect of low temperatures and draws attention to the complexity of the ageing phenomenon.

Extensive discussions with stakeholders have revealed two opposing views on second-life batteries: firstly, that a safety framework can be put in place to allow the use of second-life LiBs in DLiBESS, so long as the full history of the batteries in their first life applications is known and/or they can be tested effectively. Discussions with INERIS representatives reinforced the critical nature of first life information in second-life applications, a point made very clearly in a recent report from the organisation [36].

The second, more radical, view shared by some respondents is simply that the safety of such cells can never be guaranteed, and hence that second-life LiBs should not be employed under any circumstances in DLiBESS.

5.2 Consumers purchasing or building their own SLDLiBESS

Cells, modules and battery packs are freely available from, for example, online sites (see Appendix 3). The source of second-life modules is most likely to be EV battery packs but it is unlikely that a typical home will require a full EV battery pack (see Section 8.6 for analysis of DLiBESS systems available on the market). Hence consumers building DIY SLDLiBESS are likely to buy cells and/or modules directly, or packs which they can disassemble, online or directly from e.g. ATFs. Where this is the case, it raises concerns over the potential lack of skills, knowledge and training of consumers if they are to avoid electrocution, arc flash explosion (the disassembly of EV packs is complicated and hazardous), thermal runaway (and hence toxic gas release, fire and/or explosions inside the domestic environment) or chemical hazards when handling EV batteries and being exposed to the electrolyte. In addition, any information consumers may have acquired is likely to have come from hobbyists (such as social media groups) comprised of people who may lack knowledge of LiB technology[9] [134] and the associated risks and hazards. A knowledge of system-level safety is key here and highlighted by e.g. the industrial scale LiBESS incidents in South Korea, many of which were due to system-level failures [135].

The issue of variability of second-life LiBs is addressed in section 8.1, and it is not clear if consumers will know the importance of matching SoH. If there is variability in SoH across the modules and cells of a SLDLiBESS, cell balancing would be critical to avoid overcharge [136], or overdischarge: hence the design and operation of the BMS of such packs would also be safety-critical. A key question would then be, if the BMS was supplied with the pack, was it repurposed by competent personnel? If the BMS was built by the homeowner, would they have the appropriate knowledge and expertise to ensure the BMS is fit-for-purpose? For example, the explosion of the LiBESS in Arizona (see Appendix 1) clearly showed the importance of cell-level rather than module or stack–level monitoring. It is also not clear if consumers will realise the necessity for maintenance or have the necessary knowledge to effect it if they do.

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[9] As a simple example, a common misconception is that a lithium ion battery discharges to 0V: in fact, the cell voltage should not be taken below c.a. 2.4V (so even a discharged battery still retains considerable electrical energy) to avoid overdischarge and the attendant copper dissolution and re-deposition.

Finally, modules and packs acquired by consumers may be damaged, at SoH < 50% and/or have lithium metal plating and hence have a greater potential for failure. Thus, in February 2021, a mid-terraced house in Western Avenue in Acton [137] was badly damaged by fire caused by the failure of LiBs being charged for two electric bicycles: the bicycles had been converted using kits sourced from the internet. The Western Avenue fire was the second such major fire involving LiBs in London within 3 months. This shows the inherent risks of the public purchasing lithium-ion cells or modules from less reputable vendors and assembling energy storage devices from them[10].

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[10] Such fires are becoming more prevalent, see https://www.london-fire.gov.uk/news/2021-news/july/fire-investigators-issue-urgent-warning-over-fires-involving-e-bike-batteries/; https://www.ny1.com/nyc/all-boroughs/news/2021/12/18/fire-officials-say-e-bike-battery-caused-deadly-fire-in-east-village

6 Gateway testing of second-life LiBs

6.1 State of Health, State of Safety and Remaining Useful Life

Gateway testing is employed for two reasons: (1) to assess if a pack or modules are suitable for reuse, remanufacture or repurposing in terms of the requirements of the second-life application, i.e. to assess Remainder-of-Useful-Life (RUL) and (2) to assess if the pack or its modules are safe for second-life application, i.e. to assess State-of-Safety (SoS).

Gateway testing initially involves (see Figure 7) visual inspection of the pack and modules for damage such as dents or perforations, leakage of coolant (if employed) or electrolyte: such defects render the pack suitable only for recycling. Assessing RUL can be achieved through access to the first life data stored in the EV BMS providing it is sufficiently comprehensive. The BMS data are also regarded as essential with respect to ascertaining SoS, e.g. to determine the number of times overcharged & overdischarged or operated at extremes of temperature [21]. However, as pointed out in Zhu et al [21], the ability to accurately determine the RUL based on the historical information will depend on the role of the company that is responsible for repurposing. For example, LiB manufacturers are likely to have more information on the degradation of their LiBs to base an assessment on compared to third-party repurposers, which is why a relationship with the EV OEM is desirable.

Figure 7 Schematic illustrating the gateway assessment of second-life lithium-ion batteries. From [21].
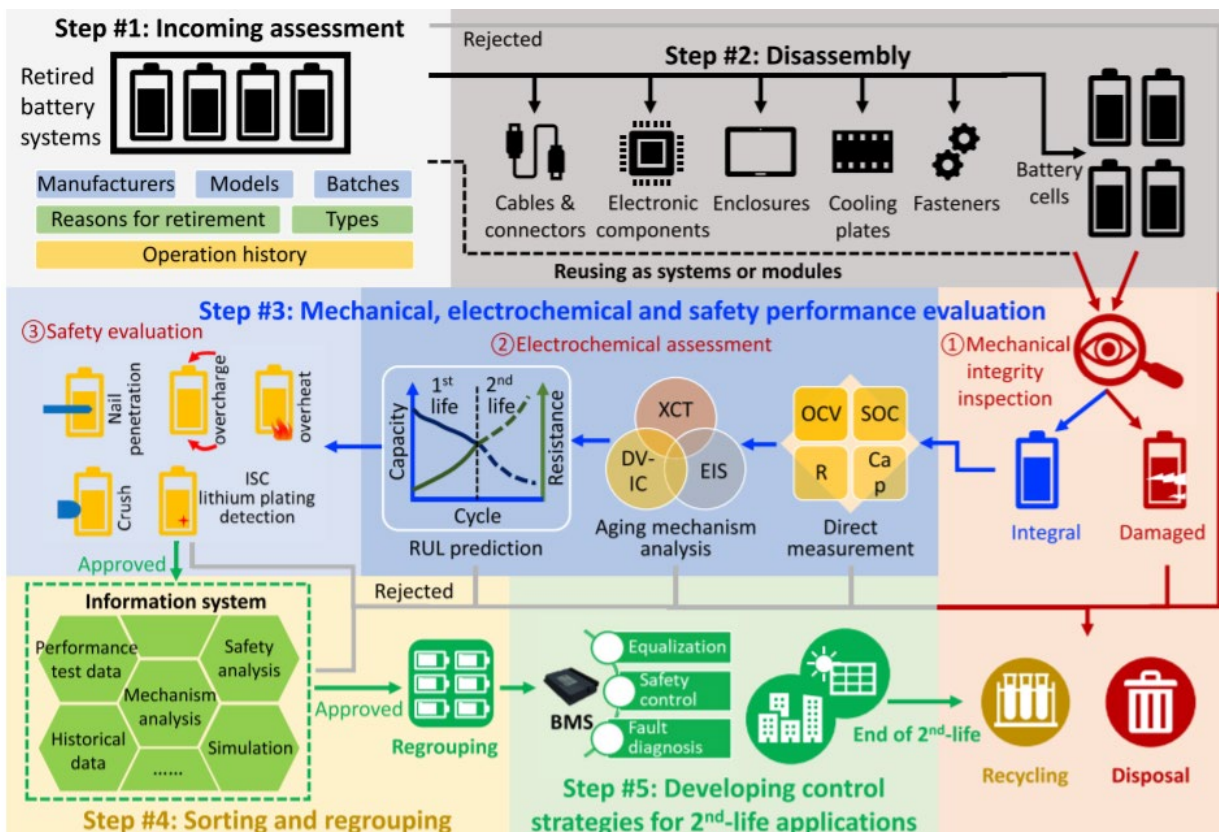
As part of assessing RUL, the SoH is also generally determined: as was stated in section 3.3, the most common definition of SoH is the ratio of the current maximum capacity of a cell, module or battery, Q_C, to the maximum capacity when new, at BoL, Q_{BoL}, expressed as a percentage (see Figure 8):

$$SoH = (Q_C/Q_{BoL}) \times 100\% \quad (1)$$

Figure 8 Representation of a LiB at (a) Beginning of Life, BoL, and (b) after ageing

(a)   (b)
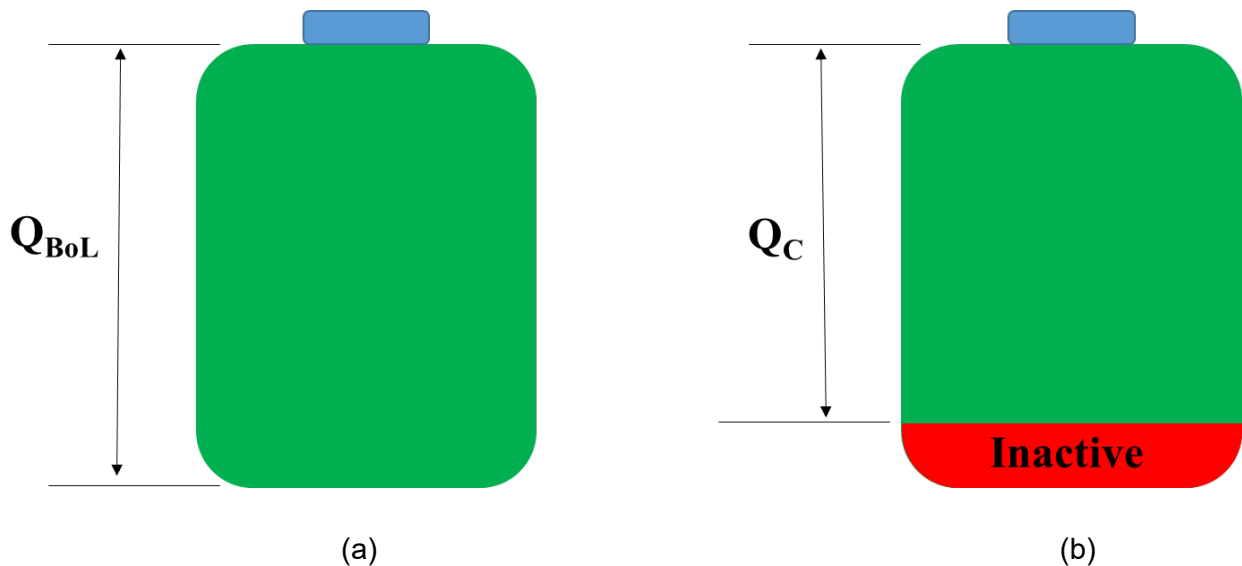
The SoC of a new cell is determined from a calibration curve of cell voltage vs charge (known as capacity, in Ah): this is produced by detailed testing and only valid as a result of rigorous quality control producing cells with extremely tight specifications. The determination of the SoH of a cell once it has been used is extremely challenging [138] as the charge corresponding to 100% SoC cannot be determined.

An alternative numeric definition is in terms of the internal resistance, or impedance which can be measured for both new and used cells. In alternating current (AC) theory, the impedance, Z, is given by Ohm's Law:

$$Z = V/I \quad (2)$$

Where V is the voltage and I the current. The resistance R is the specific case of (2) when applying a direct current (DC):

$$R = V/I \quad (3)$$

The internal resistance or impedance of a cell is that of all the components of the cell, current collectors, electrodes, separator, electrolyte and wires. When measured by DC techniques it is the internal resistance and when measured by AC techniques it should be referred to as the internal impedance, but resistance is the term most usually employed. Increasing internal resistance causes power fade and eventual EoFL [139, 140].

A typical technique employed to measure internal resistance, along with other critical parameters, is Electrochemical Impedance Spectroscopy (EIS) [141]. This involves applying a sinusoidal voltage perturbation (with a fixed max amplitude of 3 – 10 mV) between the anode and cathode of a cell. The equipment then measures the current response in terms of the time-dependence of the magnitude of the current and its phase shift as a function of the frequency of the imposed signal. The cell is modelled as an assembly of electrical components, known as the equivalent circuit approach, e.g. resistors (the internal resistance and the resistance to charge transfer at the interfaces), capacitors (representing the electrode/electrolyte interfaces or "double layers"), constant phase elements ("leaky capacitors") and inductances (the wires). By varying the parameters of the components in an iterative manner, the actual EIS response of the cell is compared and finally matched to that produced by the equivalent circuit model, and values for the various cell components extracted. The method relies on the testing of a significant number of modules at a number of temperatures and SoC. The data so obtained is then employed to create a look-up database to inform the formulation of the equivalent circuit model [142]. This is specific to the cell under test: the procedure has to be repeated for each cell type.

SoH is then defined in terms of the current internal resistance R_{IRC} and the resistance at BoL, R_{IRBoL}:

$$SoH = (2 - [R_{IRC}/R_{IRBoL}]) \times 100\% \quad (4)$$

One DC approach to measure internal resistance is the current off method in which the cell is charged and the current supply switched off: the ratio of the drops in voltage and current are then employed to determine the resistance via Ohms Law (3). Similarly, the current switching method measures the ratio of the changes in current and voltage when switching from charge to discharge.

Additional tests include measurement of the open circuit voltage and battery capacity, the latter typically via cycling between charge and discharge.

With respect to the State-of-Safety of a LiB, however, the problem is that there are currently no generally accepted tests to measure SoS, as will be discussed in section 8.2.1. In addition, there are *currently* no UK codes, standards or regulations relating to the safety and fitness-for-purpose of second-life lithium-ion modules or packs to be employed in SLDLiBESS, but this situation will change with the introduction, and adoption by the UK, of the IEC standards currently being drafted (see section 8.2.1).

Future developments and the state of the art for gateway testing are discussed further in the paper by Zhu et al [21] which reviews promising developments such as automatic battery disassembly and inspection, non-destructive testing using acoustic waves and data-driven machine learning approaches.

6.2 Examples of gateway testing

Several organisations and initiatives were identified through the research where approaches to gateway testing LiBs have already been developed. This included an EV recycling company (EV Recycling) and the UK Energy Storage Laboratory (UKESL) project [143, 144]. The gateway testing methods they employ to assess the safety and SoH of modules and packs are discussed in detail below.

Visual inspection is invariably the first check to assess any physical abuse and hence possible crushing of cells, coolant or electrolyte leakage, as well as corrosion (and hence water penetration).

Case study: UKESL approach to gateway testing

The aim of the UKESL project was to investigate the value and commercialisation of Nissan Leaf EV batteries for the stationary and portable ("roaming") electricity storage markets, but did not include domestic storage. The project produced workflows that NMUK could follow and train factory workers to do which consisted of a series of pass/fail gateway tests. At the pack level, this included visual checks for corrosion and damage, pressure tests and a BMS test. Additionally, a characterisation test is used to provide readouts of the internal resistance and the remaining capacity (as a measure of voltage or SOH), and a power test to assess its ability to charge and discharge [143]. The project facilitated the repurposing of the Leaf packs into a commercial operation.

A pack is graded based on these gateway tests and if suitable can then be reused directly in an industrial scale LiBESS. If the pack fails any tests, it is opened and examined to see whether it can easily be repaired before being retested. If the pack still fails, it is disassembled and the modules graded using EIS. The process and associated algorithms have been patented. This includes assessing parameters such as charge transfer resistance and internal resistance to check against look-up data to assess if there are any

electrochemical or electrical problems with the module, within 3 minutes. If the module fails the EIS tests, it is sent for materials recovery, although such failures have been minimal. Passed modules are sent to the battery remanufacturer, and NMUK pass on the required information on the modules along with producer responsibility. The respondent, representing a major EV battery research organisation, stated that Extended Producer Responsibility is in urgent need of clarification and it should move with the second-life cells/modules/packs from the EV OEM to the remanufacturer: further there needs to be flexibility and clarity over who carries what level of liability and when.

The same respondent replied to concerns that type tests are not valid for second-life cells, modules and packs: in their view, this critically depends upon how product safety and standards are set, and it is largely down to the remanufacturer/repurposer to ensure that the second-life batteries are safe, not just using tests, but also through rigorous control of the remanufacturing/repurposing process and system design. The risk of failure should be minimised and containment should be in place to prevent thermal runaway propagating, and it should be possible to warrant safety based on this design-for-failure concept. Overall, it would be a mistake to be too prescriptive as this would give a false sense of security and seriously restrict the flow of second-life material into a potentially important market, the technical feasibility of which has been thoroughly proven with respect to the Nissan modules and packs which have 5 – 10 years of useful life in their second-life applications and many satisfied customers. An EV OEM also expressed strong faith in the safety and durability of its second-life batteries, based on a significant body of statistical data on first and second-life failure rates and its customer satisfaction.

Case study: EV Recycling approach to gateway testing

EVRC takes EoFL EV packs and remanufactures LiBESS from them for use in a variety of applications from construction to marine, but excluding SLDLiBESS. The testing the company employs is noteworthy as it is fairly extensive:

- A Safe System of Work is created.

- The EV pack is disassembled.

- The modules are inspected visually for obvious signs of damage.

- A series of current/voltage tests are performed followed by internal measurements of module resistances, using DC methodology, and the determination of SoH using power and capacitance measurements.

- Insulation and isolation of the modules are then assessed.

- If necessary, pressure tests are also carried out.

- The BMS is replaced by an application-appropriate system as, in the company's view, retaining or revising the original BMS could be dangerous.

The company offers this testing to customers and selected outside organisations.

7 Analysis of mitigating measures for design and installation

It should be noted that apart from the gateway testing discussed in Section 6, there is currently limited information available on best practice in design for mitigating risks specific to second-life LiBs and DLiBESS. Therefore, this section builds on mitigating measures from [1] and, where possible, their relevance to second life LiBs and LiBESS.

There are four key categories of safety systems in new LiBs: the Solid Electrolyte Interface, the Battery Management System (BMS), physical safety systems and chemical additives, see Figure 9. These are described below alongside safety systems external to the DLiBESS and installation and maintenance, which should also be considered for domestic BESS. The previous BEIS report [1] presents a detailed discussion of the system-level safety strategies by DLiBESS manufacturers including measures to prevent thermal propagation between cells and control of temperature during normal operation and is therefore not discussed further in this report.

Figure 9 Safety systems in LiBs [68].
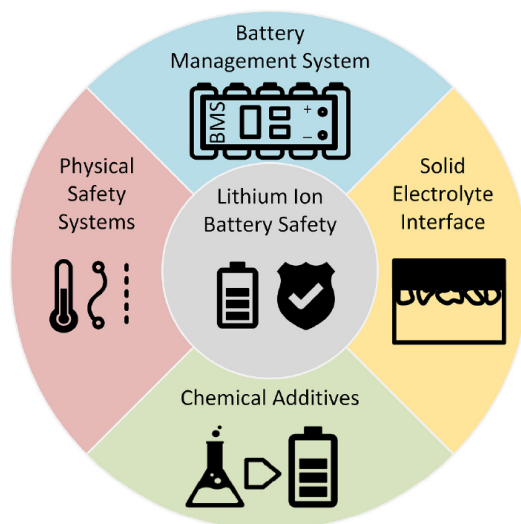
7.1 Safety systems at cell level

7.1.1 The Solid Electrolyte Interface

The SEI is the first safety "system" and is internal to the cell. When fully charged LiBs should be inherently unstable, as the graphite anodes have essentially the same potential as metallic lithium and hence should immediately and exothermically reduce the organic carbonates employed in the electrolyte [145] and continue to do so. The reason that this process stops is the formation of the SEI during the first charge. Thermal runaway is generally initiated when this protective barrier is damaged in some way. In the manufacturing process, LiB cells are usually held at low states of charge (SoC) for long periods of time during the cell manufacture to ensure complete SEI formation.

7.1.2 Physical safety systems

The physical and chemical safety systems employed at cell level in LiBs are designed to cut one of the two circuits in a battery: the internal ionic circuit (movement of lithium-ions) and the external, electronic circuit (movement of electrons). Physical safety systems include: safety vents, thermal fuses such as temperature cut-off (TCO) circuitry (e.g. protection circuit modules, PCM's) which form part of the BMS, positive temperature

coefficient (PTC) thermistors and shutdown separators [16]. As the temperature approaches the melting point of a shutdown separator, the pores close up and become blocked, preventing the movement of lithium-ions and hence shutting down the electrochemical processes in the cell.

Blast caps are typically manufactured from aluminium-ferrum alloy which has a weakened area defined by engraving, designed to break under excessive gas pressure. The gas vents to the outside of the cell via vent holes. As well as releasing gas, by positioning the vent foil below and linked to the cathode connector, when the vent breaks it breaks the connection to the external circuit (acting as a current interrupt device, CID) hence stopping electrochemical reactions from taking place.

An example of a PTC comprises conducting ceramic particles in a crystalline, non-conducting polymer matrix. Under normal circumstances, the ceramic particles form a conducting path. However, if the temperature of the thermistor increases due to the local temperature rising, or due to the passage of out-of-range current (causing Joule heating), the polymer matrix softens and the particles move apart, increasing the resistance: eventually the PTC becomes non-conducting.

7.1.3 Chemical additives

Chemical additives form up to 5% of the solvent [16, 146] are usually commercially secret and are critically important to the safe functioning of LiBs. They have a number of functions, which include: facilitating SEI formation and/or improving SEI structure, enhancing the thermal stability of $LiPF_6$, improving the conductivity, viscosity and wettability of the solvent or protecting the Al current collector from corrosion. Perhaps most importantly, they are a key aspect of the in-built safety systems in an LIB along with the physical systems, in that they can: reduce solvent flammability, provide overcharge protection/toleration and terminate battery operation under abuse conditions (shutdown additives). Some specific examples of additives are presented below.

The electrolyte, $LiPF_6$, exists in chemical equilibrium with PF_5:

$$LiPF_6 \leftrightarrow PF_5 + LiF \quad (5)$$

The PF_5 so produced can attack both the organic solvent and the SEI, producing gaseous products and reducing the stability of the latter. A simple solution to this problem exploits Le Chatalier's Principle by adding low concentrations of LiF to the electrolyte (e.g. 0.05 wt.%) to force the equilibrium (5) to the left [147].

The alkyl carbonate solvents employed in lithium-ion cells are the most thermally sensitive component of these devices, and their reaction with exposed lithiated anodes and/or with the oxygen produced as cathode structures collapse are responsible for the heat and gas generation. The flashpoints of the typical solvents dimethylcarbonate (DMC), ethylmethylcarbonate (EMC) and ethylenecarbonate (EC)[11] are 15, 22 and 33°C [147], and flame retardant additives can be employed to lower the flammability of the electrolyte. Both halogenated and non-halogenated organic phosphorous compounds have been used, but toxicity and environmental concerns have led to more focus on the latter: the organophosphorus compounds generate radical scavenging species in fire which remove the hydrogen and hydroxyl radicals essential to maintain combustion. They can also act to form a char which acts as a barrier between the liquid and gas phases to inhibit combustion [16, 147].

Overcharge protection is achieved using redox shuttles (RS). If the BMS malfunctions, redox shuttles can provide additional protection against overcharge. These species are reversibly oxidised and reduced (i.e. the shuttle is rapidly oxidised to the cation radical $RS^{\circ+}$ which in turn can be rapidly reduced back to the neutral species) at the cathode and anode, respectively, during charging, providing a safe ionic internal short circuit which

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[11] All solvents contain EC as it is believed to be essential for the formation of the SEI.

converts the current supplied to heat. Once the potential of the cathode surpasses the reduction potential of the shuttle, the shuttle is oxidised:

$$RS \rightarrow RS^{\circ+} + e^- \quad (6)$$
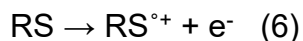
where e^- is an electron. The radical cation then diffuses to the anode where it is reduced back to RS:

$$RS^{\circ+} + e^- \rightarrow RS \quad (7)$$

The potential of the cathode is pinned at that of the shuttle: at lower potentials, the redox shuttle is inactive. Examples of redox shuttles are phenothiazines, triphenylamine, metallocenes and dimethyl benzene. Thermal runaway typically occurs at SoC > 140% [148] and hence potentials for overcharge protection can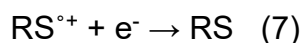 be significantly higher than the nominal voltage of the cell, and range from 3.52V to 4.90V ([16, 147] and references therein).

Shutdown additives are oxidised at high potentials to release a gas (typically CO_2) which triggers a CID or safety vent: they may also polymerize on the cathode surface to prevent further overcharge ([16, 147] and references therein). Examples of these species include xylene, cyclohexylbenzene, biphenyl and 2,2-diphenylpropane.

7.2 The Battery Management System

Another major safety system is the BMS. The purpose of the BMS is to ensure as far as possible (i.e. BMS are known to fail, as may be seen, for example, from incidents involving the overcharge of EVs [16]) safe operation and to facilitate longevity, monitor state of function in the form of SoC and SoH, provide alerts for causes of concern such as high temperatures and cell imbalance, and indicate EoFL [149]. The BMS should prevent overcharge (thus, when charging a smart phone, the BMS disconnects the battery from the charger when 100% SoC is attained) and overdischarge, both of which can lead to potentially catastrophic failure [147]. The BMS should prevent cell imbalance: e. g. cells with lower SoH in terms of lower capacity and/or higher internal resistance tend to show a higher voltage than other cells when the battery is fully charged. This means that they can be repeatedly overcharged, leading to accelerated ageing and possible thermal runaway. Thus, selecting cells or modules with similar SoH is critical in reusing, remanufacturing and repurposing batteries.

The sophistication and functionality of the BMS depends strongly upon the application: hence reuse and remanufacturing of a pack will not require the BMS to be replaced or modified, however, repurposing will require replacement or modification to an application-specific BMS. Thus, the BMS would have to adjust the operational limits at the cell level to take into account ageing. Ideally, the BMS of a battery employing second-life cells should ensure that as far as possible individual cells were monitored and maintained within their operational limits (as opposed to monitoring just at module or rack level: such low monitoring granularity relies on the very high quality control over the manufacture of new cells) e. g. as with VDE-AR-E 2510: 2017 (See section 8.2) and DNV RP43. The latter is quite specific on the granularity of monitoring: "For Li-ion batteries … the voltage measurement of each cell is crucial for a reliable operation. If the voltage measurement fails, overcharging or deep discharge of certain cells in a battery module cannot be detected. In some cases, this can lead to thermal runaway. For this reason, the voltage measurement of every cell should be checked for plausibility and if this plausibility check fails, the operation must be stopped immediately." [150]. However, disassembly to cell level after EoFL is generally regarded as too expensive and in many cases not practicable (see section 3.4), and hence will be stopped at module level. The granularity of monitoring will then depend on the wiring of the modules: for example, the Envision-AESC modules employed in 2018 and after Nissan Leafs will only allow monitoring down to parallel pairs of cells [151].

In the view of a major EV battery research organisation, the economics of second-life LiBs are on a knife edge not least because the gateway testing/triaging of modules and packs is labour intensive, but also the potential requirement to replace EV BMS with a second-life application-specific system are costly. However, the same organisation estimates that around 90% of the functionality of the EV BMS is focussed on the functioning of the EV, which is not relevant to second-life and the remaining 10% simply concerns reporting parameters (such as voltage, current and temperature) and simple switching functions. Thus, it was suggested that, with respect to reuse and remanufacturing, if it were possible to embed a simple code into the BMS to allow repurposers access to this reporting & switching functionality via a simple interface it would reduce costs significantly. In contrast, an INERIS report [54], questions whether this would be possible given the disparity in language employed by different EV OEMs in their controller area networks (CAN) protocols, and the fact that CANs are almost non-existent in stationary storage applications, where Modbus and Ethernet protocols are common.

There are also several other control and energy management strategies specific to second-life LiBs to consider [21]. As a result of the difference in energy and power capabilities between first and second-life LiBs, optimal battery sizing and appropriate control strategies are necessary to smooth the power output, to avoid overcharge/overdischarge, and to extend the cycle life of the second-life battery systems. Additionally, although the challenge of cell and module balancing and inconsistences are generally considered during gateway testing and assembly of the second-life application based on the LiBs current status, growing inconsistencies during future operations needs to be solved by active equalization strategies that can quickly reduce cell/module inconsistencies during use. Lastly, advanced fault-diagnosis algorithms for fast detection of internal short circuits, lithium plating, gas generation, etc., are also particularly relevant for second-life LiBs due to the increased risk. According to Zhu et al [21] several fault diagnosis methods have been developed for EVs but their effectiveness for second-life applications requires further validation.

7.3 Safety systems external to DLiBESS

Given the risk of fire, or the explosion of the white vapour produced by cells in thermal runaway in a DLiBESS, then the question arises of whether DLiBESS systems should be co-located with some form of smoke detector and/or gas sensor and fire detection. One European DLiBESS manufacturer does require a volatile organic compound (VOC) sensor to be co-located with its DLiBESS: however, this was not the case in general. One manufacturer that employs both new and second-life cells stated that such sensors were unnecessary as the supplier of its second-life cells had an excellent safety record and this was supported by its own gateway testing. Additionally, the manufacturer provides information on safe operation of its DLiBESS to homeowners, and safe installation guidelines to installers as well as operating an approved installer scheme.

The only EV LiB manufacturer at the time of writing in the UK employs conventional aspirated smoke detection in its plant. However, there are three sensor systems specifically marketed for LiBs, two of which are relevant to DLiBESS.

The first is a non-aspirated system and relies on the detection of vented gases via solid-state VOC sensors to provide early warning of thermal runaway (defined as a rapid temperature rise).

The second is an aspirated system drawing air through a pipe with perforations at appropriate places down its length. The air sample is then drawn past blue and red light emitting diodes (LEDs): the blue light is scattered from small droplets/particles and the red from large, respectively, with both forward scattered and backscattered light being detected and providing information.

Both systems rely on the release of gases via blast caps prior to ignition: as such they cannot provide any forewarning with pouch cells as these generally tend to simply burst with no pre-venting of gases. The detection of gases vented from prismatic and cylindrical cells depends upon the pressure setting of the vents: if too high, the cell could already be beyond the point of no return and hence in thermal runaway.

It has been suggested that combining results from these gas sensors with information from voltage, current and temperature could allow multi-sensor based algorithms to help achieve better safety management [21].

7.4 Installation and maintenance

It is also important to consider the locations in the home to avoid placing a DLiBESS[12]. This includes any location with a significant fire load, a main access route, bedrooms or roof spaces, in addition to ensuring that air can circulate around the DLiBESS to avoid overheating. As a result of the potential consequences of the hazard, rather than the risk, of thermal runaway in LiBs, the US NFPA 855 standard and the AS/NZS 5139:2019 Australian and New Zealand standard do not permit DLiBESS in the domestic space (see section 8.3). Currently, there are no requirements for the location of DLiBESS in the UK, which is generally left up to installers. If the cells in a DLiBESS go into thermal runaway and the system is located in a confined space such as a roof or the fuse cupboard under the stairs, a vapour cloud explosion could be the result. Discussions with various fire and rescue services revealed that roof voids provide an effective means of spreading fire to rooms beneath as well as adjacent houses. Further, the presence of a DLiBESS in a loft or cupboard on an upper floor could provide an unknown hazard to the fire and rescue services (FRS), as there is currently no requirement on householders to inform their local FRS of the installation of a domestic energy storage system. Thus, a fire on the floor below could send the storage system into thermal runaway posing a major hazard to both occupants and first responders in terms of fire, toxic gases and explosion. DLiBESS in under-stair locations could represent a significant obstruction to emergency egress.

In general, roof spaces and lofts do not have fire detection systems and are often employed as storage spaces that incorporate significant fire loads: in addition, the ventilation systems in modern properties often have units in the loft that take, filter and distribute air around the house, and hence would facilitate the effective distribution of battery gases from cells in thermal runaway.

There was some confusion amongst respondents as to whether or not local building control should be informed when a domestic LiBESS system had been installed. It was stated that such notification was required by one person who was Head of Building Control at a major city council, whilst other qualified persons stated this was not the case. Section 11.1.1 of the IET Code of Practice Electrical Energy Storage Systems (2nd edition) seeks to clarify this and states that "Larger projects will require notification", however, "larger" is not defined.

There is some requirement for signage associated with LiBESS. Thus, the IET Code of Practice Electrical Energy Storage Systems (2nd edition), Appendix C states: "In many circumstances, particularly for larger installations, a suitable warning sign at the main incomer (and other generators where fitted) should also be considered to warn the emergency services that a battery pack is installed on the premises." Suggested signs are given including "Battery installed on premises" to be located at main incoming switchgear and a battery voltage warning sign if the voltage exceeds 60V DC. Additionally, although there is currently no requirement for signs to provide shut-down instructions, nor is there any requirement in the code for the installation of an audible alarm to alert homeowners to

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[12] UK fire and rescue services are concerned that DLiBESS have been located under the main staircase and in the loft.

an emergency, these have been identified as further mitigating measures in the literature [152, 153].

Monitoring and maintenance is another key aspect to ensuring safe operation of DLiBESS. According to correspondence with installers, some DLiBESS are subjected to regular maintenance, while other installers monitor the performance of the system via the BMS and engineers are sent to the home to repair or replace the system as required. The recently published BS EN 62485-5 standard, discussed in section 8.2, provides recommendations and guidance for maintaining DLiBESS.

8 Codes, standards and regulations

The safety of most second-life LiBs falls under the scope of the UK General Product Safety Regulations 2005. A summary of the codes, standards and regulations relevant to DLiBESS employing new LiBs is presented in a previous BEIS report [1]. This section reviews these in relation to second-life batteries along with codes, standards and regulations developed specifically for second-life batteries. Based on stakeholder consultation, and considering the nascency of the market, there was some uncertainty amongst respondents in terms of the codes, standards and regulations governing their testing and fitness for purpose, and the legality of their transport.

It should be noted that this section deals only with those codes, standards and regulations that are directly applicable or relevant to second-life LiBs, it is not an exhaustive list of all standards relevant to DLiBESS.

A description of the BSI committees and their remits can be found in Appendix 2.

8.1 Second-life LiBs and type tests

At the present time, there are two methods of assessing batteries and their component cells and modules. The first approach is typified by the Underwriters Laboratories (UL)[13] standard **UL1974** which covers the sorting and grading process of battery packs, modules and cells (and electrochemical capacitors) that were originally configured and used for other purposes, such as electric vehicle propulsion, and that are intended for a repurposed use application. UL1974 requires that *all* the cells or modules to be employed in a repurposed battery are tested, and that any that fall out of specification are discarded (see section 8.3).

In contrast, all relevant European and International Electrotechnical Commission (IEC) standards (which currently cover only new LiBs) are founded upon "type tests". Such tests rely on a sample of cells, modules and/or packs being representative of the type, an assumption that is largely valid when dealing with LiBs produced by OEMs where strict quality control standards ensure conformity with respect to performance and physical characteristics such as cell impedance and SoH. Such type tests are the cornerstone of EU and UK product safety, and hence CE/UKCA marking. The majority of these tests were formulated before the concept of second-life. However, type tests on second-life cells, modules or packs from a batch cannot be taken as representative of others in the batch due to the wide variability in ageing and its consequences, and the possibility that disassembly from the original pack and reassembly during remanufacturing/repurposing has introduced defects and/or unbalanced units. In essence, an EV LiB has a demanding life, e.g. 1000 charge/discharge cycles over 5 – 10 years, operating at temperatures that can be between -20C and +70C and with routine fast charging [154].

As a simple illustration of the effect of ageing see Figure 10, which shows data from research conducted by the Newcastle University ReLiB team. The modules at BoL had a capacity at 100% SoC of 66.2Ah: as can be seen, the modules at EoL showed capacities from 49.4 to 57 Ah (75% - 86% SoH defined as the ratio of nominal maximum capacity to the maximum capacity at BoL). A single module from the pack is thus clearly not representative of the "type" in this case.

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[13] UL is an accredited standards developer in the US and Canada.

Figure 10 SoH of the modules in a 2011 Nissan Leaf battery pack, purchased second hand in 2018
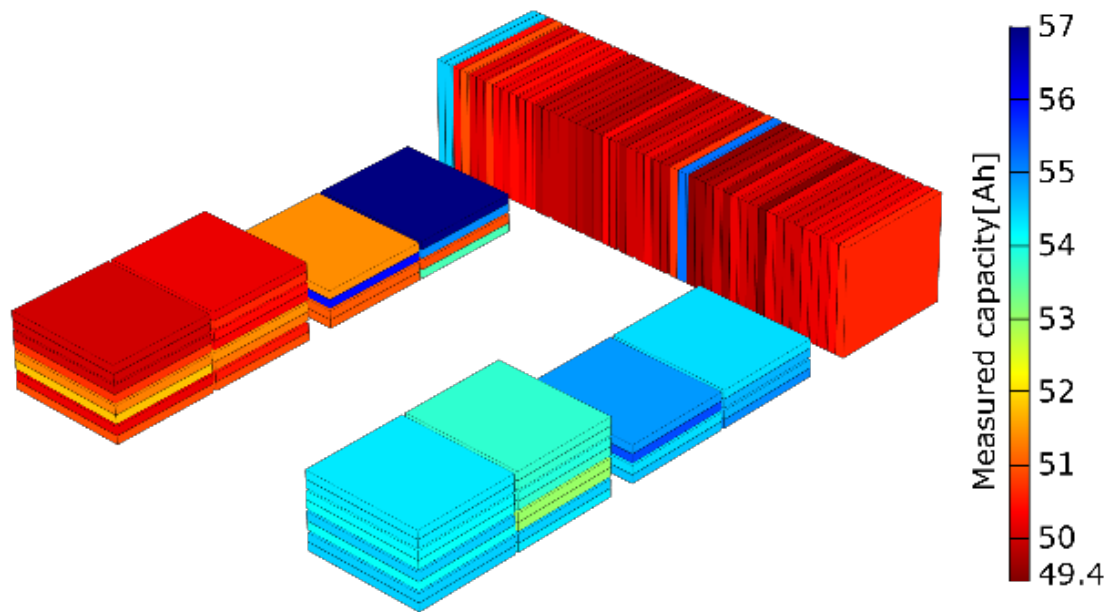
s

P. Das, M. Ahmeid, S. M. Lambert and Z. Milojevic, Faraday Institution ReLiB project unpublished results.

8.2 Standards in the UK and Europe

No EU, UK or IEC standards currently address the use of second-life batteries specifically, though there are several standards in development. This section therefore begins by discussing the range of existing standards applicable to systems employing both new and second-life cells.

BS EN 62933[14] covers electrical energy storage (EES) systems: parts 1 - 5 define terms, cover testing, environmental issues, specify safety considerations and describe human safety aspects**. BS EN 62933-5-2** covers the safety of DLiBESS, but not explicitly SLDLiBESS; though it is foreseeable that this could incorporate second-life LiBs in the future.

The first edition of BS EN 62933 states that a system test program for domestic BESS (indoor use) needs to be addressed in a different manner to that of a large complex (outdoor) utility system. 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.

BS EN 62619 (Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for large format secondary lithium cells and batteries for stationary and motive applications) specifies type tests at cell, module, pack and system level for the safe operation of LiBs in industrial scale applications, including stationary applications. Most DLiBESS manufacturers test their LiBs according to BS EN 62619. The standard includes external and internal short circuit, impact, drop, thermal abuse, overcharge and forced discharge tests: to pass these tests, no fires or explosions should occur following failure. In order to pass the system level tests, the BMS should prevent overcharging and should terminate charging when the temperature exceeds safe limits: in addition, inducing thermal runaway in a single cell should not cause propagation to other cells. Given the rigour of the BS EN 62619 test standard, it is therefore often

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[14] When a standard exists as a British standard (BS) based on a European (EN) or international (IEC) standard, the BS version is referenced.

recommended to apply BS EN 62619 instead of **BS EN 62133-2** (this specifies the requirements and tests for the safe operation of portable sealed secondary lithium cells and batteries containing non-acid electrolyte, under intended use and reasonably foreseeable misuse) for the LiB part of domestic energy storage systems (using new LiBs). Currently, second-life LiBs are not covered under BS EN 62619, and the standard relies on type tests. The standard is currently being amended, but is not expected to include second-life LiBs [155].

BS EN 62619 covers various applications and therefore includes requirements that are common and minimum to the applications. To cover specific LiB risks for electric energy storage systems, IEC has recently published **IEC 63056** (adopted as BS EN 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) which complements BS EN 62619 and includes specific safety requirements and tests for LiBs used in electrical energy storage systems under the assumption that the battery has been tested according to BS EN 62619. BS EN 63056 does not cover the use of second-life batteries.

BS EN 62485-5 (Safety requirements for secondary batteries and battery installations. Part 5: safe operation of stationary lithium-ion batteries) was published recently and is highly relevant to DLiBESS in general, whether employing new or second-life lithium-ion cells. It applies to stationary storage systems connected to the grid having a maximum DC voltage of 1500V. The standard concerns primarily electrical safety, including protection against electric shock and prevention of faults such as short circuits. Section 9 is focussed on the enclosures employed to accommodate LiBs but concerns larger LiBESS rather than DLiBESS, as does section 11 on identification labels and warning notices. However, a number of sections make explicit reference to LiBs: thus section 7 makes explicit reference to preventing lithium metal plating caused by operation at low temperatures and overcharging, and preventing overdischarge. Section 8 discusses the safety measures to be taken in the event of the release of electrolyte, smoke and fire. Section 13 states explicitly: "To ensure the safe operation of a stationary battery, regular inspection is required" and lists the signs of deterioration of LiBs that could signal a "safety critical state" and should trigger the withdrawal of the battery from use. However, the same section states "Regular inspection and monitoring of batteries in service shall be performed in accordance with the recommendations contained in the battery manufacturer's instructions" and, as was discussed in section 7.4, routine maintenance including visual inspection, is not carried out by all DLiBESS manufacturers.

In contrast to existing UK and EU standards, the German national standard **VDE-AR-E 2510-50:2017** [156] seeks to address DLiBESS directly and is compliant with EU practice. This standard also addresses potential gaps in the current international standards regarding LiBESS. Thus, for example, it was stated by a DLiBESS manufacturer that no international standards require mandatory tests to account for spontaneous internal failures (very much specific to LiBs). Only one of the DLiBESS suppliers consulted require an audible alarm and VOC detector[15] to be installed with a DLiBESS, and VDE-AR-E 2510: 2017 is the only European standard requiring the BMS to monitor all cells and to shut down the DLiBESS if one or more cells are operating outside of their safe parameters. The revised VDE-AR-E 2510 standard is also likely to include this requirement, which is especially relevant to systems using second-life LiBs. The standard explicitly excludes second-life batteries, as these are to be specifically covered by new standards.

Additionally, there is a notable German guide that covers the safety aspects of DLiBESS (although not SLDLiBESS). The voluntary guide "Safety guidelines for Li-ion home battery storage systems" was released in 2014 [157] and was prepared with the participation of

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[15] A collocated VOC sensor is also required by the Austrian standard OIB Richtlinie 2 – Brandschutz 2019

many institutions including the German industry association for electrical manufacturers (BVES), the German Solar Industry Association (BSW-Solar) and the International Solar Energy Society, German section (DGS, Deutsche Gesellschaft für Sonnenenergie e.V.). Together these associations represent the majority of the stakeholders for LiBs. The guide seeks to educate installers and other stakeholders about the hazards associated with DLiBESS at cell, battery and system level by listing the hazards, the acceptable outcome if there is an incident caused by the hazard, preventative and corrective measures and the relevant codes, standards or regulations. The guide is focussed only on the DLiBESS itself and does not cover any wider issues such as location in the home or emergency planning.

8.2.1 Standards in development

IEC Committee TC21 is drafting **IEC 63330** (Requirements for reuse of secondary batteries) which will link to IEC 62933-5-3. A new standard, **IEC 63338** (The reuse of secondary lithium and nickel metal-hydride cells and batteries after extraction from the application they were first placed on the market with) is also under development. Both IEC 63330 and IEC 63338 will cover the use of second-life LiBs.

IEC 63330 specifies the procedure for assessing the safety of second-life LiBs to be employed in applications other than that of their first life (assumed to be in EV battery packs). The current draft provides a simple, high level flow chart of the route from the initial production of the cells and assembly into the first life battery, through EoFL, and assessment for second-life through to ultimate end-of-life and recycling/disposal. The assessment includes suitability for second-life application as well as safety. IEC 63338 provides high-level guidance on the safe and environmentally benign re-use (intended as a general term for second-life application) of LiBs.

A 2021 BSI report [138] identified second-life testing as a gap in standards, and the invalidity of type tests on second-life batteries is made explicit in Clause 6.3 of BS EN IEC 63338 (19 Jan. 2021 draft). However, both it and BS EN IEC 63330 rely completely on the BMS data collected during first life, without any gateway testing, to ensure the safety of reused, remanufactured and repurposed LiBs. Clause 6.3 states that non-destructive (i.e. non-type) testing of batteries is "not established at the time of publication": and this remains a major gap in the standards. The information required by BS EN IEC 63330 includes (but is not restricted to): extreme values of temperature, charge and discharge current and charge & discharge voltage. BS EN IEC 63338 requires more information: as well as explicitly requiring information on overcharge and overdischarge (which is implied in the information required by BS EN IEC 63330) and overcurrent & overtemperature, details of insulation failure, accidents and storage conditions (e.g. storage period, environment, etc.) are also required.

The reliance on EV OEMs to make BMS data freely available to repurposers (the re-use and remanufacture of EV battery packs is likely to involve the OEM directly and may be carried out by the OEM, see Section 3.3) was greeted by considerable scepticism by a number of respondents from EV manufacturers. Further, the failure to keep the link between the VIN and battery serial numbers by the EV OEMs discussed in section 3.3, is a challenge that needs to be addressed. Both BS EN IEC 63330 and 63338 require the company looking to place second-life LiBs on the market to form direct links with the EV OEM, and BS EN IEC 63338 goes further in requiring contractual links to be sought where the OEM intended the batteries for reuse. In fact, EV OEMS are forming collaborations with repurposers to ensure the smooth transfer of information and material to produce a range of products including: SLDLiBESS, industrial LiBESS and solar nanogrids [158]. Some EV OEMs are going even further and incorporating the principle of whole life from production through first and second-life to recycling [158] into battery design.

BS EN IEC 63338 also introduces the novel concepts of "intended" and "unintended" reuse, and requires the original manufacturer (e.g. the EV OEM) to label their batteries

accordingly: if any of the required information is not available, the cells, modules or batteries are not to be reused.

Lastly, **BS EN 62933-5-3** is currently a draft standard under development and specifies the requirements for prevention of safety deterioration caused by initially non-anticipated modifications to electrochemical based EES systems. The standard is essentially concerned with the retrofitting of cells, modules or other parts to an *existing* BESS, but does include the "loading (of) reused batteries", although details are yet to be publicly available. It was suggested by one respondent that it is important that the difference between repair and modification should be made plain in this standard: thus, a repair is the like-for-like replacement of faulty components (such as cells, modules, inverters) for remanufacture, as opposed to a modification for repurposing. BS EN 62933-5-3 is to be applied in addition to the requirements in BS EN 62933-5-2.

8.3 Codes, Standards and Regulations outside the UK and Europe

While no standards currently address second-life LiBs in the UK and Europe, standards do exist elsewhere, most notably the first edition of UL1974 (Standard for Evaluation for Repurposing Batteries) which was published in 2018. Similarly to the UK, UL has a suite of standards concerning LiBs and LiBESS which are discussed below in addition to notable codes, standards and regulations in other countries.

UL1974 is a manufacturing process standard and, as stated in Section 8.1, it is the factory repurposing or remanufacturing the batteries that is certified under the standard, not the batteries themselves. An important definition in UL1974 is the "incoming sample" or battery pack when dealing with first life LiBs in an EV. This is the battery pack at EoFL and prior to disassembly and subsequent repurposing. UL1974 requires that the tests carried out on the cells in the pack when new conform to the appropriate standards, e.g. UL2580 and IEC62660-3. The EoFL pack is visually examined and the information on the pack, e.g. reason for withdrawal from service, length and nature of storage and handling history also assessed. The SoH of the pack is also assessed using data from the BMS, which includes:

- Average and extreme values of current, voltage and temperature.
- Out of specification values of these.
- Total times or number of instances at extremes or out of specification.
- Total number of charges and discharges.
- Total times or numbers under charge and under discharge.
- Total number or type of error messages.

This reflects the fact that the SoH of a battery is far more complex than represented by the simple in equations (1) and (4) in section 6.1. The information required for compliance with UL 1974 is more comprehensive than that required by the draft BS EN IEC 63330, but omits the additional requirements of BS EN IEC 63338 (insulation failure, accidents and storage conditions) although these may be encompassed in the information contained in the specified error messages. If the BMS data offers no cause for concern (and hence rejection of the pack into materials recovery) then the next stage of the assessment is employed which is the following tests:

- Open circuit voltage.
- High voltage isolation check.
- Capacity.
- Internal resistance.

- Check BMS controls and protection components (if BMS to be re-used).

- Discharge/charge cycle test whilst monitoring temperature, voltage and current.

- Self-discharge.

These tests may also provide reason for rejection of the pack: if the tests are passed then the pack is disassembled to the smallest unit that will be employed in the repurposed battery, typically the module. The modules and the bus bars, wires etc, are inspected for damage. The modules from the disassembled pack are then subjected to the same tests and the standard recommends a 6σ limit or narrower for the repurposed battery specification values: modules that fall within the same 6σ range are placed in the same grade and hence are "balanced and appropriately matched" and used in the same repurposed battery. Batteries and/or parts falling outside the specification set by the repurposing manufacturer will be rejected. The standard gives suitable tests to assess each parameter should the manufacturer not have its own tests. Cells assembled into repurposed batteries should be of the same model and from the same original manufacturer. The standard does not cover the process for remanufactured batteries, which are also referred to as refurbished or rebuilt batteries.

To comply with the US **NFPA 1** fire code, second-life batteries must be repurposed by a UL 1974 compliant battery repurposing company before used in a LiBESS.

If the cells or modules conform to UL1974 then the LiBESS comprised of these must meet standard **UL1973**. As with BS EN 62619, UL1973 allows for the simple fact that failures will occur and hence the tests include assessment of the ability of the system to withstand failure. UL 1973 is a comprehensive safety standard for batteries that includes the cell, pack, BMS and system criteria. It requires a Failure Mode and Effect Analysis (FMEA), the BMS is required to go through a functional safety investigation and there is a comprehensive suite of tests including single cell propagation. UL 1973 is similar to an end product standard.

In addition to the UL standards for second-life LiBs, the US organisation SAE International is drafting **J2997** (Standards for Battery secondary use). The aim is to "develop standards for a testing and identity regimen to define batteries for variable safe reuse. Utilize existing or in process standards such as Transportation, Labelling and State of Health", though there is limited information available in the public domain.

Another relevant test method, applicable to both new and second-life DLiBESS, is **UL9504A**. This was developed to address safety concerns identified by the building codes and the country's fire service, namely: BESS installation instructions; installation ventilation requirements; effectiveness of fire protection (integral or external) and fire service strategy and tactics. The test method is aimed at determining the capability of battery technology to undergo thermal runaway and to allow the subsequent evaluation of the fire and explosion hazards & hence the fire and explosion protection required, rather than focussing on assessing the safety of the cells. It is applicable to DLiBESS as well as industrial LiBESS, and could be applied to SLDLiBESS as it is assessing the safety of the *system*, rather than cells or modules, and provides data that can be used to mitigate or prevent propagation of thermal runaway between cells and modules.

The test method involves a sequential series of destructive tests at cell, module and LiBESS level, each test carried out a total of four times to assess reproducibility. Individual cells are heated using a heating pad: if they go into thermal runaway, then modules are tested: if they also fail then full LiBESS level testing is carried out. In each case, tests are fully monitored on a tick-list basis, e.g. thermocouples are employed to monitor temperature, and gasses are monitored to ascertain composition. The tests facilitate a number of design strategies and standard operating procedures to be developed. For example, the determination of: separation distances between units to minimize fire propagation; separation distances between units and enclosure walls; potential of fire

spread to overhead cabling; fire protection strategies; ventilation requirements via the measurement of deflagration potential and heat generation and fire service strategy and tactics. It is worth re-iterating that UL9540A is intended to inform the development of safety systems and procedures, it does not demand action be taken on the basis of the tests. Thus, it can be claimed that a LiBESS "conforms to" UL9540A in that the tests have been carried out, but may not actually have been acted upon in terms of addressing any issues arising from the tests.

A number of countries are addressing the issue of the hazards specifically represented by the location of DLiBESS – but none currently specifically address SLDLiBESS. For example, the US **NFPA 855** states that:

"BESS shall only be installed in the following locations:

1. In attached garages separated from the dwelling unit living area and sleeping units in accordance with the local building code.

2. In detached garages and detached accessory structures.

3. Outdoors on exterior walls or on the ground located a minimum of 3 ft from doors and windows.

4. In enclosed utility closets and storage or utility spaces."

However, NFPA855 assigns the prevention of thermal runaway entirely to the BMS: but once the chemical reactions responsible for thermal runaway have replaced the electrochemical processes of normal operation, thermal runaway cannot be prevented by any form of electrical intervention under the control of the BMS such as switchgear, or physical intervention by e.g. thermal fuses.

In addition, cities in Arizona have introduced new laws requiring permits for homeowners installing DLiBESS [159].

The Australian **AS/NZS 5139:2019** "Electrical installations — Safety of battery systems for use with power conversion equipment" standard states that [160] "Pre-assembled integrated BESS shall not be installed: (i) in ceiling spaces; (ii) wall cavities; (iii) on roofs not specifically deemed suitable; (iv) under stairways; or (v) under access walkways. In areas of domestic or residential electrical installation, pre-assembled integrated BESS shall not be located in habitable rooms. Suitable areas may include garages, storage rooms, dedicated battery system room and verandas". If DLiBESS are excluded from the domestic space in the UK, their protection against water ingress will have to conform to BS EN 60529.

A final, notable development is that on 21 June 2021, the Chinese government proposed regulations to prohibit the use of second-life EV LiBs in large industrial stationary storage systems following a number of industrial LiBESS fires, although they will still be allowed in small industrial LiBESS [161]. According to reports this will be under review until a 'breakthrough in battery consistency management technology and a sound power battery performance testing and evaluation system' is developed [162].

8.4 Second-life LiBs as waste

The Waste Batteries and Accumulators Regulations 2009 require individuals or companies who place batteries on the UK market to register as producers, and this then requires them to take back waste batteries. However, there is considerable confusion as to whether second-life LiBs should be considered as waste under these regulations, which were drawn up before LiBs became ubiquitous in society and before their use in second-life applications was conceived. The Environment Agency, as part of the consultation process, stated that there is a general misunderstanding that second-life batteries employed in an application such as a LiBESS are not waste. The Agency's view is that LiBs removed from an EV, or other device, are waste. They may or may not achieve end-of-waste status if

they meet the End-of-Waste test in Article 6 of the EU Waste Framework Directive[16] [163]. Due to the confusion, any queries concerning LiBs as waste are currently dealt with on a case-by-case basis by DEFRA, the Environment Agency and OPSS. This is not considered by these organisations to be a sustainable practice as battery reuse increases. Reuse is due to be considered as part of domestic regulation reforms, and is also covered, as discussed below, by the EU Batteries Regulation which was passed by the EU Parliament in March 2022.

In the consultation process, the Environment Agency expressed concerns over the safe disposal of batteries from DLiBESS. The DLiBESS manufacturers will be responsible for this at the end of the systems' life[17]: the concern is where consumers have built their own system, and whether or not they understand their responsibilities. Thus, once the modules in a DIY SLDLiBESS have to be replaced, they will become waste. If the waste weighs more than 4 kg (as an example, a 2018 Nissan Leaf module weighs more than 8 kg) it would be classified as an industrial battery. As such, they must be transported to a suitable ATF for recycling in accordance with the regulations covering the transport of dangerous goods (see Section 8.5 below).

8.5 The sale and transport of second-life LiBs

The market in second-life LiBs, and hence the remanufacture and repurposing of LiBs, depends critically on the transport of the batteries. This includes start-up companies and consumers assembling DIY SLDLiBESS who rely on online sites. In general, there was considerable uncertainty amongst respondents regarding the application of transport requirements on second-life LiBs.

LiBs are classified as dangerous goods under UN 3480 [164] and hence require transportation in accordance with the requirements of the agreement "Accord relatif au transport international des marchandises dangereuses par route" (ADR [165]). Any LiBs classified under UN3480 (lithium-ion batteries) and UN3481 (lithium-ion batteries contained in equipment) must pass the type tests detailed in the UN Manual of Tests and Criteria Part III sub-section 38.3 (UN38.3). There are eight of these type tests, including thermal, vibration, shock, external short circuit, impact and overcharge, which are tests to destruction. All cells, including those used in equipment, are required to have passed these tests, although certain tests are waived when the batteries are to be installed in a vehicle that offers suitable protection. UN38.3 requires a number of batteries to be tested, half of which are subjected to one test cycle and 25 half cycles: this is based entirely on new LiBs as these are known to change with further cycles after the first. Moreover, as discussed in section 8.1, type tests are not suitable for second-life LiBs.

At the time that UN38.3 was formulated, the possibility that LiBs would have a second-life was not envisaged: it was assumed that, as was the case with lead-acid batteries, their use (in EVs) would be followed by recycling. Hence UN38.3 testing only applies to *new* LiBs as a design type test to allow for classification (a lithium battery may only be transported once it has passed the 38.3 tests, although there are some exceptions): it does not apply to second-life LiBs. However, where a battery is reworked, the changes may result in it being considered a new battery as defined in 38.3.2.2.

The ADR is transposed into UK law as Regulation 5 of the UK Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations 2009 [166]: "No person is to carry dangerous goods, or cause or permit dangerous goods to be carried, where that

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[16] The Waste Framework Directive explains when waste ceases to be waste and becomes a secondary raw material, and how to distinguish between waste and by-products. The Directive also introduces the "polluter pays principle" and "extended producer responsibility".

[17] The regulations also allow for other producers to take responsibility under certain circumstances.

carriage is prohibited by ADR …, including where that carriage does not comply with any applicable requirement of ADR or RID" [167]. The ADR regulations have a number of exemptions depending on battery size; however, if the total load of LiB on a vehicle weighs more than 333 kg, then the transport must conform fully with the requirements of ADR:

- The driver needs to hold an ADR licence and have received the relevant training.

- The packaging must have the correct markings and labels.

- Transportation documents are required.

- Vehicle marking and equipment, and driver equipment are required.

- The LiB must be packed according to the appropriate packing instruction.

There are three packing groups in the UN recommendations for solids and liquids (Packing group I – high hazard, II – medium hazard, and III – low hazard). As lithium batteries are articles, they are not assigned a packing group. However, where UN tested packaging is required, packaging for articles will be tested to the packing group II level for solids unless otherwise indicated:

II. **Undamaged** batteries require packing according to packing instruction P903.

II. **Damaged and defective** batteries require packaging in accordance with packing instruction P908 that has passed the required UN tests (drop and stack tests).

I. **Damaged, defective and batteries liable to rapidly ¨disassemble¨** require packaging in accordance with P911 at the packing group I level and additional testing as agreed with the Vehicle Certification Authority (VCA) on behalf of the Department of Transport. Essentially, a test must be done that demonstrates that with the LiB content in thermal runaway, any fire/explosion and excessive heat is contained by the package. This is an expensive test to do.

Critically for DIY SLDLiBESS, the ADR requirements do not apply to the public collecting and transporting LiBs.

8.6 The EU Batteries Regulation

Representatives from across the UK battery industry attending DEFRA consultations expressed strong support for the EU Batteries Regulation (EU BR) when published as a draft, and hence it is likely that the UK will broadly align with the regulations [168].

The full weight of the EU BRs will be applied to battery energy storage systems with capacities greater than 2 kWh which will be classified as " industrial batteries": as the average annual domestic electricity demand for a Profile Class 1 home in the UK is 1800 – 4300 kWh (i.e. 5 – 12 kWh of electrical energy per day [169, 170]), it is likely that DLiBESS will be classified as industrial batteries and hence be governed by UK versions of the EU BRs if adopted. Of the 13 UK DLiBESS systems listed on the Solarguide website [170], only one is less than 2 kWh and eight are scalable to 10 kWh or more.

Focussing only on the LiB-specific safety aspects of the EU BRs: under Article 12, stationary BESS will require documentation showing that the systems are safe via a number of type tests, ranging from evaluation of resilience to thermal shock, thermal cycling, mechanical shock and internal short circuit, to overcharge, over-discharge and over-temperature protection systems. This is highly reminiscent of the UL 9540A test standard employed in the USA. However, the EU BRs relies on type tests. Additionally,

Article 14 requires that BMS can store the data deemed to be required to determine the SoH and expected lifetime (including remaining capacity, capacity fade, remaining power capacity and power capacity fade, round trip efficiency, cooling demand, self-discharge history and Ohmic resistance or impedance) and that such data are made available to facilitate re-use, repurposing or remanufacturing, but there is no explicit requirement for this information to have been employed to ascertain if second-life LiBs are fit-for-purpose for use in BESS. Furthermore, the data required does not include parameters that can indicate abuse such as maximum/minimum temperature, maximum charging current, as required by IEC 63330.

Article 64 states that the Commission will implement an electronic information exchange system to store and make available battery information: operators who place industrial LiBs on the market will make the information on the battery available through this resource. However, the information to be stored appears to be only beginning-of-life data, and there is no explicit link to the data discussed under Article 14.

Article 59 explicitly concerns the repurposing and remanufacture of industrial and EV batteries with respect to the availability of data and particularly information on safety relevant to handling and testing. It also seeks to broadly address the key question of whether LiBs at the end of their first life are classified as waste, and hence subject to the appropriate regulations. Thus, the article requires that an operator proposing to employ a battery in a second-life application proves that the battery is not waste by providing evidence that the SoH has been evaluated or tested in a member state, that the purpose of the battery is validated by an invoice or contract of sale or transfer of ownership, and that evidence is provided of the appropriate protection against damage during transport.

Under Article 65, by January 2026 every industrial battery, irrespective of application, will have to have an "associated battery passport", linked to the EU data system described in Article 64. When the battery "changes status" responsibility for the information held on the data system transfers to the new owner.

8.6.1 Potential barriers to the adoption of the EU Batteries Regulation in the UK

The Eurobat organisation which represents companies covering all aspects of the LiB value chain welcomed the draft EU BR, but expressed concerns over restrictive aspects of the proposed regulation, including the requirements to use minimum levels of recycled materials and materials recovery targets, and the incorporation of design for second life application [171].

The German Energy Storage Association (BVES) has also suggested that "The proposed EU Batteries Regulation are far-reaching, progressive and likely to shape the battery market in the EU in the 2020s" [170]. However, the same association expressed significant concern over the fact that the draft regulation does not cover the testing of second-life LiBs and, along with other German national organisations, has also expressed concern at the apparent drive to reuse EV batteries inherent in the proposed regulation at the expense of considerations of safety. In 2020, BVES published a position paper on the proposed EU Battery Regulations in which it raised its concerns that type tests were not valid for second-life LiBs [172].

The EU BR will not cover millions of industrial batteries in use now and in the immediate future, and its relevance to second-life LiBs is not clear. However, once the regulation is in force, it may be that changing the application from EV to industrial may require a new producer declaration and the batteries would be covered.

As stated at the start of this section, the broad acceptance of the draft EU BR in the UK is not shared elsewhere. Whilst welcoming in principle the EU BR, the German Energy Storage Association (BVES), along with the German Association of the Automotive Industry e.V. (VDA) and the German Electrical and Electronic Manufacturers' Association (ZVEI) have responded at various levels [172] to a standardisation request from the EU

which, in the group's view, has deficiencies in many safety topics relevant to second-life batteries. This includes the testing of second-life LiBs which remain a gap in standards and, in particular, the validity of type testing as discussed in Section 8.1.

Lithium-ion cells must operate within strict operational limits if catastrophic loss via thermal runaway is to be avoided through e.g. lithium plating, lithium dendrites, copper deposition and internal short circuit, excessive heat etc. In addition, as discussed above, a LiB, unlike its lead-acid counterpart, has chemical, electrical and mechanical safety systems, and these require monitoring as do current, temperature and voltage. Thus, unlike a lead-acid battery, a LiB requires a BMS, and is an *electrical device* that should, in the view of the German industry group, have equivalent requirements for electrical safety as the Low Voltage Directive (implemented as Electrical Equipment Safety Regulations in GB). This was a view widely shared by stakeholders consulted as part of this research.

The group raises particular challenges with article 59, whereby independent operators would be given access to the BMS for "the purpose of assessing and determining the SoH and remaining lifetime". In addition to concerns over OEMs' willingness to release such potentially valuable intellectual property, the group was concerned that it may not always be the case that operators would have the necessary skills and expertise to be able to use the information for the purposes specified.

With respect to LiB energy storage systems employing new cells, the German industry group believes that, although a lithium-ion-specific standard is overdue, there is no gap, the existing standards just need to be applied intelligently. However, there are a number of gaps in the current relevant international codes, standards and regulations for second-life lithium-ion batteries.

Key challenges for the success of the EU BRs, and the use of second-life modules and packs in general, will be: how effectively first life information will be retained with the modules and packs during their life journeys; whether EV OEMs will grant access to this intellectual property and whether there will be a general acceptance that the gateway testing and/or access to key first life information of these devices is fit for purpose.

9 Conclusions

9.1 The market

The market for second-life DLiBESS (SLDLiBESS) is difficult to predict which was evident by the absence of detailed market information. While a number of stakeholders consulted as part of this study use second-life batteries in their LiBESS, these are predominantly for industrial applications and evidence suggests there is currently limited use in domestic systems. Therefore, in order to assess the potential market for SLDLiBESS, the following drivers and barriers were reviewed as reasonable indicators:

- **The market for DLiBESS.** Market analysis suggests that the UK DLiBESS market is a nascent but growing industry, with estimated capacity at 38 MWh in 2019 expected to rise to between 128 – 339 MWh by 2024 [2]. Consumer drivers are likely to be maximising use of onsite generation, such as solar, in addition to buying and selling electricity. This should be considered in light of rising electricity costs and the falling costs of LiBs.

- **Environmental and economic drivers for second-life LiBs.** The extraction and processing of the metals required by LiBs is both expensive and harmful to the environment. Additionally, it is estimated that there could be 75,000 to 105,000 end of first-life (EoFL) EV LiBs in the UK by 2025, which represent potential environmental and safety waste hazards. In contrast, reuse, remanufacture or repurposing could extend battery life by 7 – 10 years, minimising waste and delaying or reducing materials recovery which is currently both energy intensive and limited in capacity.

- **Availability of second-life LiBs.** While the projected surplus of second-life LiBs is good news for the DLiBESS industry, the latter is unlikely to soak up the surplus and there will have to be significant innovation and investment in materials recovery. This will likely be driven by material supply and/or regulation, with the 2022 EU Batteries Regulation proposing to significantly increase the recovery of certain metals from LiBs in addition to requirements to incorporate certain levels of these recyclates into new LiBs. While likely to drive materials recovery, this could be at the expense of second-life.

- **Price of second-life LiBs.** It is currently both costly and labour intensive to test and triage EoFL batteries due to a lack of standardisation among EV OEMs. In addition, the falling cost of new LiBs means the economic incentive for reuse and repurposing may become less attractive.

9.2 Risks and hazards

The hazards represented by LiBs can be severe if they are not properly mitigated. The hazards associated with second-life LiBs are broadly the same as for new LiBs, but the probability of failure may be higher with the former due to the effects of ageing and unknown stress and/or abuse during the LiBs first life application. However, this remains an ongoing area of research and there is currently insufficient information available to determine either the likelihood of an age-related failure or the effect of that failure with confidence.

The capacity loss of LiBs is generally considered to be linear, with EoFL typically around 75-80% state of health (SoH) and final end-of-life around 50-60% SoH. However, at some point there is a change in and/or an additional ageing mechanism which leads to an increased ageing rate. The time at which this occurs is referred to as the "knee" where

severe and potentially dangerous deterioration is expected to occur and the battery has reached its final end-of-life. Currently this point is difficult to predict, but can occur at a higher SoH than expected. Cycling at normal rates or calendar ageing does not have a significant impact on safety; however, cycling at low temperatures or high rates can have a detrimental effect upon stability and can significantly reduce the temperature at which thermal runaway occurs and consequently increase the risk of thermal runaway. In addition, this is shown to increase the risk of internal short circuits and joule heating.

It is for this reason, and due to the potential variance of SoH between EoFL LiBs (including within the same pack), that a sample of second-life LiBs should not be taken to be representative of the batch. Therefore, the safety of second-life LiBs cannot be reliably assured by type tests, which form the basis of all current international and European standards. Instead, an assessment is required for each LiB prior to use in a second-life application, including SLDLiBESS.

9.3 Best practice and standards

The re-purposing of LiBs is a nascent global market which has led to some uncertainty amongst respondents in terms of the codes, standards and regulations governing their testing, fitness for purpose, and transport. There are currently no UK or European standards specifically for second-life LiBs; however, both IEC 63330 and IEC 63338 are being developed to address this gap. IEC 63330 will specify the procedure for assessing the safety of second-life LiBs to be employed in applications other than that of their first life, and IEC 63338 provides high-level guidance on the safe and environmentally benign re-use of LiBs. Additionally, the EU Batteries Regulation contains requirements for second-life LiBs, including for first-life data to be made available in the battery management system (BMS) to facilitate re-use. Outside of the UK and Europe, UL 1974 (Standard for Evaluation for Repurposing Batteries) covers the sorting and grading process of LiBs that are intended for a repurposed use application.

Current practices include a variety of methods to measure state-of-health and/or reliance on detailed information retained in the BMS employed during first life (i.e. the EV BMS). The engagement of EV OEMs in the latter has yet to be assessed, but is a critical factor. This information may include parameters such as: extreme values of temperature, charge and discharge current and charge & discharge voltage, details of insulation failure, accidents and storage conditions, total times or number of instances at extremes or out of specification, total number of charges and discharges, total times or numbers under charge and under discharge and total number or type of error messages. Gateway testing to assess the health of second-life LiBs includes: measuring capacity, internal resistance and self-discharge and performing a discharge/charge cycle test. This information should then also be used to balance and match LiBs in a second-life application. However, **there is currently no widely-accepted test methodology for assessing the safety of second-life LiBs and this is a major gap in international standards.** Additionally, there remains uncertainty amongst stakeholders around the transportation of second-life LiBs.

Beyond the assessment and sorting processes discussed above, there is currently limited information available on best practice for designing LiBESS to use second-life LiBs. Additional considerations include use of a dedicated BMS for the new application, such as introducing control strategies for second-life LiBs, as well as monitoring as close to cell level as possible. The importance of monitoring at cell level was highlighted by the incident in Surprise, Arizona, and is a requirement in the German standard VDE-AR-E 2510: 2017 and DNV RP43. While both the incident and standards are applicable to new LiBs, they are particularly relevant for second-life LiBs as evidence suggests the cell-to-cell inconsistencies will increase with age.

9.4 Concluding remarks

Extensive discussions with stakeholders have revealed two opposing views on second-life batteries: firstly, that a safety framework can be put in place to allow the use of second-life LiBs in DLiBESS, so long as the full history of the batteries in their first life applications is known and/or they can be tested effectively. A second, more radical view shared by some respondents is simply that the safety of such cells can never be guaranteed, and hence that second-life LiBs should not be employed under any circumstances in DLiBESS.

Lastly, due to the fire and electrical hazards associated with LiBs, the availability of potentially untested second-life LiBs and the potential lack of knowledge (for example, with LiB ageing) and skills of consumers to mitigate the risk through testing and good system design, consideration should also be given to whether stricter requirements are needed for home-built ("DIY") DLiBESS that use second-life batteries.

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Appendix 1: A case study: the explosion of the LiBESS in Surprise, Arizona

At 16:55:20 on 19 April 2019 a smoke alarm was activated by the 2MWh LiBESS in Surprise, Arizona (Industrial sized LiBESS comprised of new LiBs). Three hours later, one of the doors of the LiBESS container was opened by first responders: the resulting explosion produced a jet of flame approximately 75 feet long and 20 feet high. Two first responders were thrown against and under the chain-link fence that surrounded the LiBESS, one coming to rest approximately 73 ft from the opened door beneath a bush that had ignited in the event and the second officer came to rest approximately 30 ft from the opened door. A third first responder was also thrown by the blast but remained within the fence. The explosion was caused by the ignition of the white cloud produced by one rack of 14 modules going into thermal runaway and resulting in a vapour cloud explosion. As discussed in Section 4.3.4, the hazard of vapour cloud explosion is directly relevant to DLiBESS.

The LiBESS

The LiBESS consisted [1] of 36 racks, of which 27 contained a vertical stack of 14 modules: the modules were numbered bottom to top. Each module comprised 14 pairs of 64Ah NMC lithium-ion pouch cells: the cells in the pairs were in parallel and the pairs themselves in series. The racks were held in two rows in a standard 50 ft x 13 ft x 12 ft steel container, very similar to a sea container except with two doors. One door was on the end of the container, the other on the side and farthest away from the first door. The energy storage capacity of the LiBESS was 1/10th of that of the Carnegie Road LiBESS on Merseyside that exploded in September 2020 [2].

Timeline

At 16:54:30 local time, cell pair 7 in module 2 failed in the LiBESS. The temperature of the electronic systems on top of racks 15 and 17 started to increase at 16:54:44 from 40°C to a peak of 49.8°C over the next 54 s. At 16:55:20 the laser smoke detection system (which would respond to smoke, vapour or fine droplets of solvent) triggered and opened circuit breakers: 30 s later, as designed, the system deployed the fire suppression agent, Novac 1230. It is now generally acknowledged that fire suppressants are ineffective with respect to the thermal runaway of LiBs in LiBESS as they offer no cooling ability (the reservoirs of these systems are also typically insufficient for the extended periods of thermal runaway). The Surprise Fire Department received a report of smoke & possible prairie fire from a passer-by at 17:41 and arrived at the scene c.a. 7 minutes later and observed a steady stream of white "smoke" issuing from the container. Unaware that the container was a LiBESS they were met by a technician who informed them that the container housed a lithium-ion battery system. Units from Peoria Fire Service including Hazardous Materials specialist arrived at 18:28 and noted low-lying white clouds of a gas/vapor mixture issuing from the structure and nearby components and drifting through the desert. The container was monitored from the arrival of the Surprise officers until it was decided to open the door around 19:00 at which point "a visible white gas/vapor mixture immediately poured out of the open door" and the explosion took place. Detailed timelines may be found in references [1][3 – 5].

The cause of thermal runaway

There are four reports on the LiBESS explosion: one commissioned by the owners (DNV GL for Arizona Public Services) [1], one for the lithium-ion cell suppliers (Exponent for LG Chem [3]) and two by Underwriters Laboratories (UL [4][5]).

The DNV GL and Exponent reports differ in terms of identifying the cause of the thermal runaway.

The DNV GL report identifies the formation of lithium metal dendrites and the penetration of the separator between anode and cathode of cell pair 7 causing a catastrophic internal short circuit. The primary evidence for this model was the presence of lithium-rich deposits on the anodes of randomly-selected undamaged cells in the LiBESS and on the anodes of undamaged cells from a sister site, Festival Ranch. The Exponent report disputes this model on the basis of the following points: (1) the separators employed were coated with a ceramic layer that would resist penetration by the dendrites; (2) the deposits were not electronically conducting (and hence could not cause a short circuit[18]) and (3) even if they were conducting, the thickness of the dendrites was insufficient to sustain the expected large current flows (i.e. they would act like a fuse).

The Exponent report did not dispute the fact that the deposits contained lithium metal in some form as it acknowledged that they were pyrophoric on contact with air, as would be expected of metallic lithium. The alternative model proposed in the Exponent report is that electrical arcing sent cell pair 7 into thermal runaway, citing the facts as evidence that (1) the position of cell pair 7 was next to arc damage on the rack framework and (2) the cells in rack 15 were being charged at 27A, but this suddenly switched direction to discharging at 4A.

As discussed in Section 5.1, lithium metal plating is associated with the operation of LiBs at extremes of temperature (e.g. ≤ 5°C) or with systematic overcharging, i.e. abuse of some form, and is regarded as highly undesirable in terms of facilitating thermal runaway. Yet neither report questions why plating occurred in an installation only c.a. 2 years old[19].

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[18] In fact, metallic lithium would react with the electrolyte in one same way as lithiated graphite anodes on first charging when the SEI is formed: the layer so produced on the metal may have been thick enough to prevent electrical conduction.

[19] It should be noted that UL have not been able to attribute any field failures of LiBESS to lithium metal plating.

Appendix 2: The BSI committees and their remits

BSI has many national committees that mirror both international (ISO/IEC) and European (CEN/CENELEC) work. **PEL/21** is responsible for the preparation of product standards for all secondary cells and batteries, irrespective of type or application. **ESL/120** is responsible for standardization in the field of grid integrated EES Systems, focussing on system aspects on EES Systems rather than energy storage devices as well as investigating system aspects and the need for new standards for EES Systems. ESL/120 also focusses on the interaction between EES Systems and Electric Power Systems (EPS).

These committees mirror technical committees within IEC (the International Electrotechnical Commission) and CENELEC (the European Committee for Electrotechnical Standardisation). Most work items are developed at the international (IEC) level, as this has the biggest member input and global co-operation. Some developments may be European specific and so will be developed at CENELEC. The UK is not permitted to endorse IEC standards when they are published: however, most are because they will be useful for users. If an IEC Standard is then adopted into the CENELEC work programme and approved, so it becomes at EN IEC Standard, the UK must endorse it. It will then become a BS EN IEC XX.

The UK mirror committees are entitled to draft new work item proposals (NWIP) and present them to the IEC technical committee, and it is most likely that project will be led by the UK. Alternatively, UK members can sit on the Working Groups developing the various international standards going through development and so UK input is considered in those discussions as well as at comment feedback on ballots. The publishing process is as follows:

1. New Work Item Proposal (NWIP) – comments and vote: approval/disapproval/abstention

2. Committee Draft (CD) – comments only – best stage to heavily redraft the standard is needed

3. Committee Draft for Vote (CDV) – comments and vote: approval/disapproval/abstention

4. Final Draft International Standard (FDIS) – comments and vote: approval/ disapproval/abstention

Appendix 3: Survey of LiB suppliers online

As of 4th June 2021, 23 suppliers were found on a popular online marketplace, some selling multiple and different types of batteries, some with multiple batteries on the same listing. The deliveries have been listed as standard and as 'other courier'. In the latter case, it was not explicitly stated if the courier was licenced to transport dangerous goods.

	Supplier	Type	Quantity	Postage	Collection	Trader type	Capacity	Date viewed	Date contacted
1	Supplier 1	Module	5	Standard delivery (£20)	free	Unknown, probably sole	30kWh (stated)	01/04/21	31/03/21
2a	Supplier 2	Module	10	Standard delivery (£15.70)	Not available	Breakers yard	Not stated	01/04/21	01/04/21
2b	Supplier 2	Module	3	Economy delivery (£19)	Not available	Breakers yard	94 Ah	22/04/21	
2c	Supplier 2	Module	> 10	Economy delivery (£19)	Not available	Breakers yard	Not stated	22/04/21	
2d	Supplier 2	Pack	1	Economy delivery (£100)	Not available	Breakers yard	75 kWh	22/04/21	
2e	Supplier 2	Module	10	Economy delivery (£19)	Not available	Breaker	56 Ah	04/06/21	
3	Supplier 3	Module	≥ 4	None	Free	Breakers yard	30 kWh (stated)	01/04/21	01/04/21
4a	Supplier 4	Pack	1	Standard delivery £40	Free	Breakers yard	7613 Wh	31/03/21	31/03/21
4b	Supplier 4	Battery	1	Standard delivery £40	Free	Breakers yard	Not stated	22/04/21	-
5	Supplier 5	Pack		Courier	Not available		73 kWh	31/03/21	31/03/21
6	Supplier 6	Pack	1	Economy delivery (£150)	Lithuania	Breakers yard	7613 Wh	20/04/21	-
7	Supplier 7	Pack	1	Economy delivery (£199)	Free	Breakers yard	Not stated	21/04/21	31/03/21
8	Supplier 8	Pack	1	Installation only	Not available	Repair	Not stated	21/04/21	01/06/21
9a	Supplier 9	Pack	1	Free or express (£10)	Free	Breakers yard	Not stated	21/04/21	30/03/21
9b	Supplier 9	Battery	1	Express (Other), Express (standard) (£10)	Free	Breakers yard	36 Wh	22/04/21	
10	Supplier 10	Pack	1	Standard international (£245)	Not available	Breakers yard	12kWh	21/04/21	-
11	Supplier 11	Module	> 4	Standard delivery (£20)	Not available	Breakers yard	2.47 kWh	22/04/21	01/06/21

12	Supplier 12	NEW starter battery	2	Standard, economy, express	Free	Parts supplier	69 Ah	22/04/21	-
13	Supplier 13	Battery	1	No delivery	Free	Possible private seller	Not stated	22/04/21	01/06/21
14	Supplier 14	Battery	1	Express delivery (standard) (£30)	Free	Possible breakers	Not stated	22/04/21	01/06/21
15	Supplier 15	Battery	1	Standard delivery	Free	Breakers yard	Not stated	22/04/21	01/06/21
16	Supplier 16	Battery	1	Standard delivery (£622.71 from California)	Not available	Parts supplier	Not stated	22/04/21	03/06/21
17	Supplier 17	Battery	1	No delivery	Free	Parts supplier	Not stated	22/04/21	03/06/21
18a	Supplier 18	Battery	1	Express (other), Express (standard)	Free	Breakers yard	Not stated	22/04/21	03/06/21
18b	Supplier 18	Battery	1	Express (Other), Express (standard) (£14.00)	Free	Breakers yard	36 Wh	22/04/21	-
19	Supplier 19	Battery	1	Express (Other)	Free	Possible breakers yard	36 Wh	22/04/21	03/06/21
20	Supplier 20	Battery	1	Economy (Other)	Free	Breakers yard	36 Wh	22/04/21	03/06/21
21	Supplier 21	Battery	1	Express (Other)	Free	Parts supplier	36 Wh	22/04/21	04/06/21
22	Supplier 22	Battery	3	Express (Other) (£8.50)	Not available	Breakers yard	36 Wh	22/04/21	04/06/21
23	Supplier 23	Battery	1	Standard Delivery (£59.99)	Free	Breakers yard	Not stated	04/06/21	04/06/21

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