CSIRO

Australia's National
Science Agency

Lithium-ion battery safety

A report for the Australian Competition and Consumer Commission (ACCC)

Adam S. Best, Kate Cavanagh, Christopher Preston, Alex Webb and Steven Howell

May 2023 | EP2023-1783

Citation

Best, A, Cavanagh K, Preston C, Webb A, and Howell S (2023) Lithium-ion battery safety: A report for the Australian Competition and Consumer Commission (ACCC). CSIRO, Australia.

Copyright and disclaimer

Important disclaimer

Acknowledgements

We would like to acknowledge funding from the ACCC for this report.

We also acknowledge Mr. Scott McGarry, Ms. Terijo Lovasz, and Ms. Suzanne Neville for their helpful comments and review of this document.

Contents

Glossary

TERM	DEFINITION
Australian Dangerous Goods Code (ADGC)	Code to manage goods for transportation and storage
Battery	Cell(s) + BMS
Battery cell	Single units. Example laptop = single pouch cell
Battery Management System (BMS)	Monitors battery health and performance, can employ safety commands such as turn battery off if overheating
C-rate (e.g., 1C)	Discharge capacity at equivalent Amps i.e. battery can be in use for 1 hour with load current of 100 Amps at 1C. 2C would be a battery discharged 200 Amps over 1 hour
Electric vehicle (EV)	Battery powered transport device (e.g., cars, e scooters, e-bikes, etc.)
End of Life (EOL)	Time signifying end of a battery's use in its application
Energy Storage System (ESS) or Battery Energy Storage System (BESS)	Whole of system energy storage including battery, inverter, wiring
Joint Accreditation System for Australia and New Zealand (JASANZ)	Regulatory body guiding standards and accreditation
Lithium Cobalt Oxide (LCO)	Type of cathode chemistry in a lithium-ion battery cell
Lithium Iron Phosphate (LFP)	Type of cathode chemistry in a lithium-ion battery cell
Lithium Manganese Oxide (LMO)	Type of cathode chemistry in a lithium-ion battery cell
National Construction Code (NCC)	Mandatory building standard for built structures
Nickel Cobalt Aluminium Oxide (NCA)	Type of cathode chemistry in a lithium-ion battery cell
Nickel Manganese Cobalt Oxide (NMC)	Type of cathode chemistry in a lithium-ion battery cell
Original Equipment Manufacturer (OEM)	Equipment or components supply from the initial manufactured product
Positive thermal coefficient (PTC)	A resettable fuse, also known as polymeric positive temperature coefficient device. Used to restrict current flow under fault conditions via increased resistance from thermal feedback
Safety of Alternative and Renewable Energy Technologies (SARET)	Fire and Rescue NSW research program. https://www.fire.nsw.gov.au/page.php?id=9401
Society of Automotive Engineers (SAE), now SAE International	United States-based, globally active professional association and standards organization for engineering professionals in various industries
State of Charge (SoC)	Capacity available within any one cycle
State of Health (SoH)	The remaining capacity, as a percentage, of the initial rated battery capacity
Thermal runaway	Internal battery overheating reaction

Executive summary

Lithium-ion batteries are now a ubiquitous part of our lives, powering our portable electronics, transportation solutions (e-scooters, e-bikes and vehicles) and, more recently, energy storage systems. A lithium-ion battery is comprised of several components including cell(s), a battery management system (BMS), wiring, external connection and, depending on the size of the device, potentially an active or passive cooling system. All components play a role in the safe operation of the device; the BMS is used to add multiple layers of safety to control a range of different failure mechanisms that can pose significant hazards to users.

In this report, many factors associated with battery operation and failure and the potential hazards that this may pose to users and the public have been considered, including:

- the role of different lithium-ion chemistries in the severity of battery failure
- the role of the BMS in electronically managing the cells within the battery
- charging of the cells
- the charger used to charge batteries
- end of life considerations, including second life, disposal, and recycling,
- the hazards posed to users and the public when a battery fails
- the standards and regulatory framework in Australia.

Through the course of this report, the following recommendations have been generated to improve user and public awareness of the hazards of lithium-ion batteries and how these may be minimised.

General recommendations

1. Development of an Australian website that provides easy to access information on smaller consumer battery products and chargers, larger home energy storage systems, electric vehicles and more. The website should illustrate examples of failures and how consumers should avoid such hazards, as well as provide practical advice on purchasing battery powered products. Mandatory labelling for all lithium-ion battery products is recommended to inform consumers for safe use and care of the battery.
2. All lithium-ion cells are recommended to be accompanied by a battery management device or integrated circuit to assist in providing safe operating conditions. This will reduce the risk of failure due to misuse or exposure to abnormal conditions that can cause cell damage and possible catastrophic consequences. Due to continuing lithium-ion battery chemistry innovation and development, problems may escalate as manufacturers continue to store more energy (i.e., increased energy density) in their products.
3. Standards bodies and regulators should consider how to adopt and implement Table 3 to inform consumers of the quality of the BMS that is managing the battery.

Charger recommendations

4. Original Equipment Manufacturers (OEMs) should provide accessible consumer advice (e.g., websites, help files on devices, instruction manuals, or other paper documentation) inside products stating to always use chargers and cables sold for/with the products rather than using generic chargers and cables.
5. Software updates from suppliers can recognise whether their device is charging with OEM product(s). If the device is charging with a non-OEM product it may inform the consumer and issue a warning, via the interface, requesting user to acknowledge that the device is being charged with a generic charger and/or cable and that damage and/or failure could potentially occur for the device i.e., phone, laptop, or other interface device.
6. Develop a star rating for all charging products, to inform consumers about the quality of the product that they are purchasing. Standards bodies and regulators should consider a rating system on a scale of 1 to 5 for respective charger controls and managements systems.
7. Chargers should come with warnings attached to their cables and/or packaging that the products should not be used indoors, confined spaces or left unattended for extended periods, i.e., 3 hours, due to the potential risk of failure and resultant fires.
8. If consumers recognise that a battery pack or device has been impacted either by an external force such as being dropped, lightning or other events, they should have the device inspected by the manufacturer or technician/electrician to ensure that all BMS components are operating correctly prior to charging.
9. Consumers have responsibility to care for charging cables to ensure that batteries can be safely charged at all times. Where intermittent charging is observed or clear evidence of damage to the cable is noticeable, the cable should be discarded and replaced with a manufacturer specified cable.
10. Issues relating to the use of home electric vehicle chargers and implications for home safety have not been considered in this report. There are many variables related to the age of a home, the electrical wiring within it, the position of the charging point of the car, charging point to be either fixed or standalone, 10 Amp or 15 Amp General - Power Outlets (GPO). This may be the subject of a further report for standards and regulatory bodies to consider.

Hazards

11. In the event of battery off-gassing, smoke or fire in a confined space, move to safety and call Triple Zero (000) to alert authorities of the fire. Where possible, callers should also clearly state it is a battery fire and identify the item type.
12. Where it is possible to fight a small battery fire, use a foam extinguisher such as CO_2, ABC dry chemical, powdered graphite, copper powder or soda (sodium carbonate) as you would extinguish other combustible fires. Call Triple Zero (000) to inform of the fire.
13. If a person(s) does inhale lithium-ion battery vent gases or smoke, or has physical contact with liquids or solid products from the fire, they should immediately report to a hospital emergency department for treatment.
14. Batteries should be charged on non-combustible surfaces and away from combustible items.
15. Consumers should not modify products with larger or additional batteries due to risk of significant catastrophic failure. Products should be used in strict accordance with manufacturer guidelines and operating instructions.

Recycling and end of life (EOL)

16. Methods and approaches for the disposal of damaged batteries are developed to inform how a battery should be handled at EOL. At present, there are no readily available methods and sources of information that the public can adopt to allow them to safely manage a damaged battery locate for appropriate disposal/recycling. There is an urgent need to address this problem.
17. No batteries (especially damaged or EOL) should be disposed into household rubbish, due to the risk of fire in household rubbish bins and garbage collection trucks. Batteries, which are intact, should be disposed of at a recycling station.
18. Battery disposal collection points need both standards and regulation to define the minimum requirement for safe collection, storage, and transport to recycling depots. Current collections occur in public places and stores which can pose a hazard to people and property in the event of fire. There should be national standards and regulations to manage these issues.
19. National harmonisation of battery recycling standards and regulations to ensure higher collection rates, but also to inform best practice for collection, storage, and transportation to recyclers.

Standards

20. Demonstrable compliance of lithium-ion batteries to either IEC 62133 (portable applications) and/or AS IEC 62619 (industrial applications) is promoted through a combination of additional guidance in standards (such as in AS 62368.1) and regulatory enforcement options such as the establishment of mandatory certification (by JASANZ accredited bodies, etc.) of products containing lithium-ion batteries to relevant standards for their product type and/or application. This approach could facilitate improved quality control of the manufactured products, reducing the likelihood of random faults resulting in hazards during a product's lifetime, and provide an elevated level of assurance that batteries are able to withstand normal and foreseeable abnormal conditions during their lifetime.

    With increased levels of (demonstrated) compliance established, the suitability of the standards/criteria applied will be more apparent through analysis of statistics of fault events (e.g., fires). In other words, if the number of such unwanted events does not decrease with increased levels of compliance, the existing standards may be further assumed to be inadequate and require revision.

21. Enforcement of existing requirements of the ADGC to ensure that cells and batteries imported into Australia, and potentially integrated into new equipment, meet the requirements of UN 38.3. The overlap between requirements of IEC 62133, AS IEC 62619 and UN 38.3 will simplify the required compliance (i.e., testing) pathway for manufacturers, importers and potentially regulators.

22. Additional testing facilities funded and established within Australia to provide sufficient capability to conduct tests on imported products to the standards nominated above, and to assist manufacturers demonstrate compliance of Australian-produced cells and batteries.

    The availability of local testing options will reduce the barrier to market to manufacturers who currently need to send products overseas for testing, which is difficult and expensive due to limitations and hazards related to transport.

    Ensured access to UN 38.3 test capability within Australia will provide a method to comply with existing transport regulations, which may be currently being avoided through *ongoing* production and shipping of *prototype* products.

23. Capability for the required tests for assessment of fire hazard such as UL9540A, from cell to unit level, is widely developed to support Australian manufacturing R&D, and safe expansion of the uptake of residential and commercial BESS. Module-level[1] testing requires substantial infrastructure due to the potential safety hazards involved in large-scale testing.

24. Reliable statistical information is gathered from emergency services to provide an accurate estimate of the risk to the community arising from battery-related incidents (i.e., fires). The information should, if possible, include the number of events, types of products commonly involved and therefore battery sizes/capacities found to present the highest risk. While likely very difficult, the compliance of involved products should be determined to assist in the review of the suitability of existing standards.

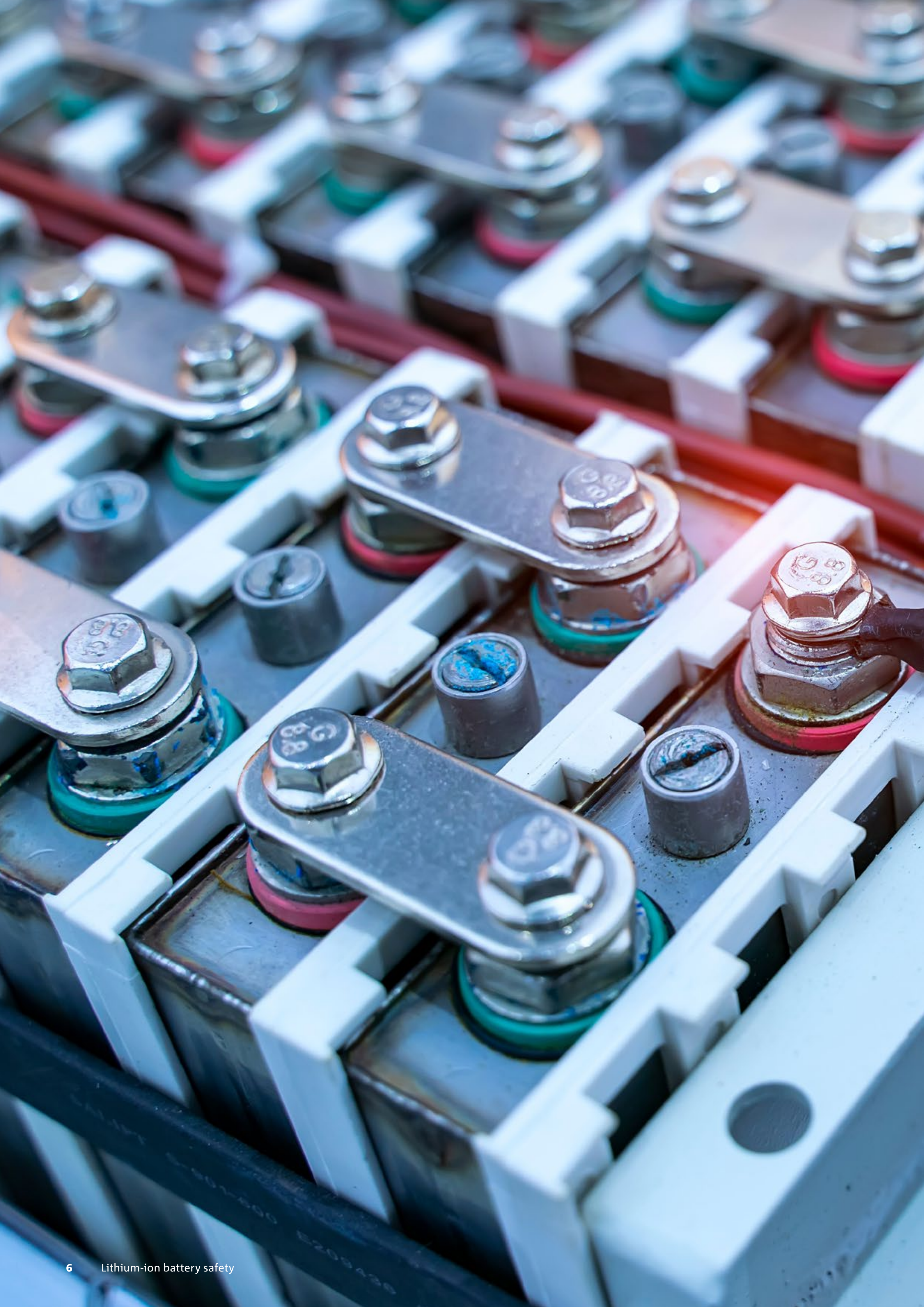
25. The collection of information would be ideally harmonised across all services operating in different states and territories to provide the largest set of data possible.

26. Where a BMS is provided as part of a product, the system should be tested accordingly, as described by AS IEC 62619 or other appropriate 'system' standard.

27. Overarching safety standards, such as AS/NZS 62368.1, should include more guidance for the selection of test methodologies for lithium-ion batteries integrated within electrical products. Requirements for mandatory (compliance) marking of batteries may assist in the forensic determination of fault events as described in Point 1 above.

28. The requirements of the ADGC are limited to testing (to UN 38.3) of individual cells or batteries prior to transport. Consideration to mandating the testing of assembled packs, if that is the form in which they are transported, should be given.

1 Modules will typically exceed 10 kWhr.



1 What is a battery?

1.1 How batteries work

A battery is an electrochemical energy storage device. A battery has two electrodes: a cathode (the positive electrode) and an anode (the negative electrode). These electrodes are separated by a medium (‘separator’) and sit in a fluid called electrolyte. Electrons are transferred from one electrode to the other in an electrochemical process called a reduction-oxidation (redox) reaction. This creates an electric current.

Specifically, a lithium battery is comprised of two active materials (cathode and anode) that store lithium ions, a separator, and an electrolyte which ‘shuttles’ the lithium ions between the electrodes and current collectors that take the electrons to/from the external circuit. A lithium-ion battery is a secondary, or rechargeable, battery in that lithium ions can be shuttled from the positive electrode (cathode) to the negative electrode (anode), described as ‘charging’, and from the anode to the cathode (discharging).

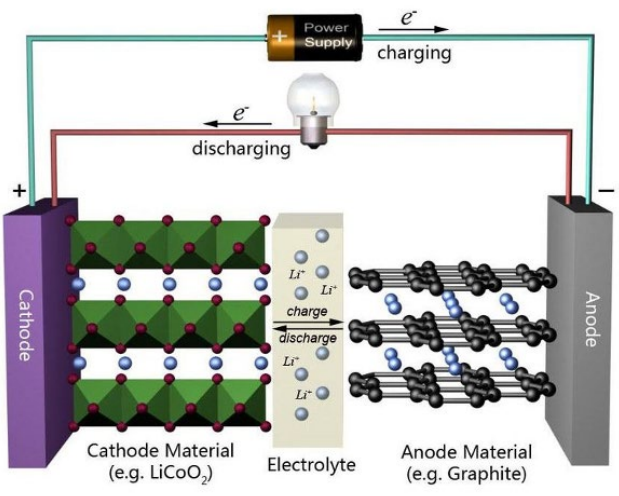


Figure 1 How a battery cell works under discharge and charge

When discharge occurs (Figure 1) a circuit is completed external to the cell via the cell contacts, and a load is applied which causes the ions to move from the anode to the cathode. Depending on the size of the load connected, the ions will move faster (with a larger load) or slower (with a smaller load). The speed the ions move is the discharge rate, or C-rate, and the resulting energy is used by whatever the battery is attached to.

If the process of moving ions from within one electrode to the other via the electrolyte was 100% efficient there would be no ‘losses’ in the system and a battery could theoretically last forever. However, due to the imperfect (electro)chemical reactions that occur both within the electrodes and the electrolyte combined with the effect of temperature, this is not the case. Over many charge-discharge cycles, the battery loses capacity. Battery manufacturers define end-of-life (EOL) as when the battery is at 80% of initial capacity in applications where power and energy (provided by the battery) are required, for example, in an electric car. This definition of EOL of a battery is arbitrary and allows for substantial functional capacity of the battery for other potential uses. Further research is in being explored for development of ‘second life’ applications discussed in Section 4.

Table 1 sets out some of the pros and cons of various lithium-ion cell chemistries. Lithium iron phosphate (LFP)-graphite cells have been the mainstay of high-power applications and are ideal in applications such as power tools. As the LFP cell chemistry has a lower cell voltage than others in Table 1, this lends to enhanced safety, especially in over discharge conditions. However, it should be noted that graphite is still used as the anode, so overcharging remains a risk in the event of issues with the Battery Management System (BMS) and/or charger (as discussed later).

2 https://www.murata.com/en-global/products/batteries/cylindrical

Table 1 Pros and Cons of various lithium-ion cell chemistries

CELL CHEMISTRY	PROS	CONS	COMMON APPLICATIONS
LFP - Graphite	Considered safest lithium-ion chemistry as one of the highest thresholds to trigger thermal runaway Robust, long cycle life High power Cheaper than Ni- and Co-based chemistries	Flat discharge curve Low energy	Stationary energy storage systems, EVs
LCO - Graphite	High specific energy	Limited specific power Cost of Cobalt Instability at high SoC	Laptops, mobile phones, tablets, cameras
LMO - Graphite	High power Safer than LCO due to higher threshold for thermal runaway	Low capacity	Medical devices, electric power trains, power tools
NMC - Graphite	High capacity High power Reduced Co content, lower cost Dominant Cathode type	Challenge of high Ni content (>80 %)– instability at high SoC High self-heating rate, thus increased risk of thermal runaway	E-bikes, medical devices, EVs, industrial
NCA - Graphite	High capacity Reduced Co content	Challenge of high Ni content (>80 %)– instability at high SoC	Medical, industrial, electric powered trains

When a cell or battery goes into an overcharge condition, the battery (graphite) anode inside is fully occupied and so any remaining lithium ions in the cell (either in the cathode or electrolyte) will plate (build up residue) onto the surface of the anode which can lead to significant heating. The nature of lithium plating can be 'mossy' (high surface area) or dendritic (needle-like), which can grow through the separator to cause a short-circuit and cell-failure. As there is significant heating associated with this condition, otherwise known as thermal runaway, it can cause gasification of the electrolyte, lead to gas pressure build up and rupture of the cell (as shown in Figure 5). In extreme cases, explosion and fire can occur if there is an ignition source close by. If the cathode is LCO, NMC or NCA (see Table 7), the oxidation state of the transition metals can be catalytic, hence causing even more violent failure.

Over-discharge within the cell is a minimal safety risk (due to the rarity of their occurrence) but can be detrimental to ongoing cell performance. If a cell or battery is over-discharged, recharging of the cell should be performed with caution. If there is any visible distortion or bulging of the cell or battery, indicating gas formation, it should be carefully disposed of.

1.2 Cell formats

Depending on the application and/or end use, manufacturers have a range of cell formats to choose from when designing a product: coin or button cell, prismatic, pouch, or cylindrical cell. Each has pros and cons, depending on the application targeted. The common packaging formats are summarised in Table 2.

Table 2 Different cell formats used for lithium-ion batteries

CELL TYPE	FORMAT	CELL IMAGE	DIMENSIONS	TYPICAL CAPACITY/ AMP HOUR (AH)	EXAMPLE APPLICATION
	Coin or button cell		Variable	Less than 1	Consumer
18650[2]	Cylindrical		18 mm (diameter) x 65 mm (height)	3-5	Consumer, Automotive
26650[3]	Cylindrical		26 mm (diameter) x 65 mm (height)	4-8	Consumer, Automotive, Energy Storage System
4680	Cylindrical		46 mm (diameter) x 80 mm (height)	10-12	Automotive
	Pouch[4]		Variable	Up to 100	Automotive, Aerospace, Consumer,
	Prismatic[5]		Variable	Up to 300	Energy Storage Systems

Each of the cell formats is designed so that in the event of failure they can fail in as 'controlled' a manner as possible. In the case of a prismatic cell, if the cell goes into thermal runaway, there is a vent release at the top of the cell that is designed to rupture to minimise gas build-up that can potentially cause an explosion and cell destruction. Pouch cells can also have a valve or other similar vent fitted to prevent these batteries from catastrophically failing. Cylindrical cells are designed with a positive temperature coefficient (PTC) switch to internally disconnect the cell in the event of a high current surge. There can also be a pressure release valve in this area that can release gases from the cell. Under extreme cases, where this feature fails or is not fitted, the internal winding can be ejected from the cell or the thin walls of cylindrical cans can potentially split under pressure, releasing dangerous materials.

Coin or button cells are a well-known hazard, especially to children who can ingest them, and have already been the subject of regulatory interventions to prevent harmful outcomes.[6]

Development of an Australian website that provides easy to access information on smaller consumer battery products and chargers, larger home energy storage systems, electric vehicles and more. The website should illustrate examples of failures and how consumers should avoid such hazards, as well as provide practical advice on purchasing battery powered products. Mandatory labelling for all lithium-ion battery products is recommended to inform consumers for safe use and care of the battery.

3 https://www.ocelltech.com/sale-34467929-lifepo4-26650-2500mah-26650-30c-2-5ah-rechargeable-cylindrical-battery-cells-lithium-ion-battery-lar.html
4 https://www.onecharge.biz/lithium-cell-format/
5 https://www.mustess.com/lifepo4-prismatic-battery-cell-3914895-50-60ah/
6 https://www.productsafety.gov.au/product-safety-laws/safety-standards-bans/mandatory-standards/button-and-coin-batteries

1.3 Emerging technologies

New electrode materials and cell chemistries are being developed by researchers and start-ups to disrupt the incumbent manufacturers. Many of these chemistries are 'high risk, high reward', translating to high technical risk, high commercial reward, and are targeted towards emerging markets, especially the disruptive mobility space. The disruptive mobility space, such as autonomous cargo planes, 'last mile delivery' drones and electric Vertical Take-off and Landing (eVTOL), all require lightweight, high-energy batteries that enable long duration flight (energy) together with high power (required for take-off and landing). Technologies which use a lithium metal anode, such as lithium/NMC and lithium-sulfur (Li-S) batteries, offer the promise of energy densities of more than 350 Wh/ kg, which is in excess of state-of-the-art lithium-ion cell chemistry, making them excellent candidates for these applications. However, there remains significant challenges in these chemistries, including control of the lithium metal anode structures, which can potentially lead to short-circuit of the cell and failure of the device.

It is anticipated there will be many new entrants to the battery space with chemistry 'solutions' that can potentially enable these technologies. However, with the emergence of novel technologies, there will be pressure on regulators such Civil Aviation Safety Administration (CASA), the United States Federal Aviation Administration (FAA) and European Union Aviation Safety Agency (EASA), which regulate and certify aircraft and various sub-systems, to develop standards and regulations that will ensure these chemistries are safe for flight, especially where the cargo is human passengers. There are a number of start-ups in this domain and success in aerospace could also see these technologies be transferrable to automotive and other application domains. It is recommended that regulators maintain awareness of emerging technologies to understand their associated challenges and risk.

All lithium-ion cells are recommended to be accompanied by a battery management device or integrated circuit to assist in providing safe operating conditions. This will reduce the risk of failure due to misuse or exposure to abnormal conditions that can cause cell damage and possible catastrophic consequences. Due to lithium-ion battery chemistry innovation and development, problems will continue to escalate as manufacturers continue to store more energy (i.e., increased energy density) in their products.

2 Lithium-ion batteries

A battery, for the purposes of this report, is defined as one or more cells that are assembled in a series (S) and/or parallel (P) arrangement to increase voltage or capacity, respectively. This may be denoted in the name of a battery pack such as 2S4P (2 cells in Series, 4 strings in Parallel).

2.1 Simple assembly of batteries

The manufacture of a battery pack includes:

- one or more cells of the preferred format and chemistry
- welding of wires to the cells to connect them in a series/parallel configuration to meet the energy and voltage of the application
- the addition of a Battery Management System (BMS)
- a cooling system (as appropriate to the application)
- external contacts and a housing for the system.

These subsystems of a battery system and considerations about how they impact on battery failure and resulting hazards to the consumers are discussed in the following sections.

2.2 Battery Management Systems (BMS)

2.2.1 BMS overview

The Battery Management System (BMS) is a critical component of any lithium-cell based battery pack, especially for high energy density and long lifespan products, as it manages the performance, efficiency, and safety of the battery system.

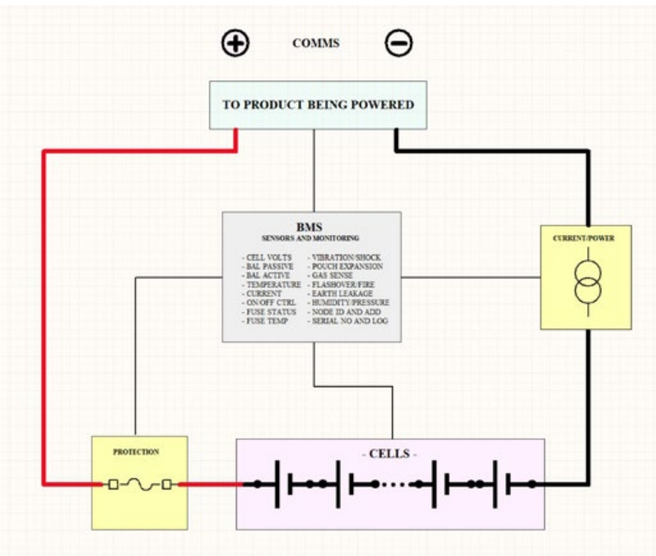


Figure 2 A basic schematic of Battery Management System (BMS)

The BMS manages the following capabilities of lithium-ion cells in the battery pack:

- Monitoring State of Charge (SoC), remaining charge in any charge/discharge cycle, and State of Health (SoH), remaining usable capacity of the battery over its useful life, ensuring that the battery operates within safe limits to avoid damage.
- Balancing the battery cells: evenly distributed charge and discharge are required for each cell to prevent over or under-charging, enabling unity through all cells equally, as the battery pack must be operated with an equal load per cell. The BMS may use passive or active balancing techniques to achieve this goal. Passive balancing is inefficient, slow, and produces a lot of heat, but is inexpensive. High performance active balancing is very efficient, fast, and produces low heat, but is costly.
- Protecting the battery and providing layers of safety: from overheating, over-charging, and over-discharging, leading to safety hazards. The BMS disconnects the battery from the load or charger if the current exceeds safe limits. Both cooling and heating systems may be employed to maintain suitable battery temperature within safe limits.
- Providing battery performance data and communications, such as voltage, current and temperature. This data is used for optimization of the system's efficiency, lifespan, history, range, and safety status.

Table 3 sets out features that the authors have associated with 4 levels of a BMS performance based on cell manufacturer recommendations and target markets: minimum, fair, good, and excellent. It is recommended that this Table is used as the starting point for a classification system for BMS that are used in lithium-ion battery packs to inform consumers as to the quality of the products that they are using. This classification system could be voluntary in the first instance and potentially standardised in the future.

Standards bodies and regulators should consider how to adopt and implement Table 3 to inform consumers of the quality of the BMS that is managing the battery.

Table 3 Recommended BMS rating classification

BMS RATING	BMS FEATURES	TYPICAL APPLICATION EXAMPLE
Minimum	Comparator-based lithium-ion balancing integrated circuit (heavily dependent on compliant charger)	Toys
Fair	**BMS Features under Minimum plus the following:** • Cells of a type with internal protection being fuse, PTC or e-fuse if suitable • Monitor the voltage and temperature of each cell and balance in a reasonable time to suit the applications charge/discharge cycle • Cells can be monitored in groups • Prevent power entering the pack when fully charged (over voltage) or over temperature • Prevent power leaving the pack when cells are over temperature or exhausted (under voltage) • A pack DC-rated fuse with appropriate separation • Designed and built to SELV (Safety Extra Low Voltage)	General consumer products, e-cigarettes, torches
Good	**BMS Features under Fair plus the following:** In addition to the capabilities above, for a system that has a need for greater quality and reliability due to the pack being used in either a higher powered, more hostile environments or extended life applications, additional features should be included in the BMS: • Quality cells with matched capability, quality control manufacture and characterised in a standard datasheet • Semiconductors rated to twice the pack input or input protection to accommodate accidental and over-voltage inputs including ESD such as lightning strikes and human generated electrostatic • Current sensing of the overall pack • Humidity sensing • Cells monitored and logged over time to gauge performance through SoC and SoH history algorithms • Sensing of cell characteristics and monitoring for cell expansion (gassing) and impact/vibration (accelerometer/MEMS) • Communications scheme to inform the application or host of the state of the cells in the pack • Inclusion of a Piezo-electric alarm and red LED indicator allowing audible and visual indication of a compromised battery	Laptops, power tools, e-scooters
Excellent	**BMS Features under Good plus the following:** In addition to the sets of capabilities above, for applications requiring high performance, safety and the ability to manage the pack condition and expectations, the BMS should include these additional features: • Designed and built to IPC2221, IPC610 and assembled to IPC6012 • Fully isolated design with very low cell leakage • Per cell monitoring including current sense • Both active and passive cell balancing • Bypass diode applied across each cell • For military, aviation or mining, MIL-SPEC, DO-series and Ex Intrinsically Safe specification as required • Additional sensors for gas (hydrogens/carbons) and ARC/Flashover light sensors (500- 900nm wavelength) • Pack switch management, including potential across DC switch and switch temperature • Positive and negative differential earth leakage detection (balanced) • Quality build with minimal cabling, high temperature rated materials and compliant protective enclosure • Authenticated wireless communications to allow both normal BMS operation and exceptions to be communicated to all parties (including emergency services) • Includes thermal management and control system • BMS can interrupt host with critical conditions rather than wait to be polled (protocol) • Acoustic sensing for high pitch gassing/hissing/crackling/popping (PDM – Pulse Density Modulation microphone) and associated FFT algorithm • Pressure sensor to sense enclosure breach or puncture	EV, military, mining, aviation

2.2.2 Wired BMS

A wired BMS uses physical wires to sense operational parameters of the battery cells, with each cell or cluster of cells connected to the BMS for transfer of voltage, current, and temperature data.

The BMS is typically wired between the managing system (host), such as the engine electronic control unit (ECU), to provide critical statistical data and operating parameters. It also has an individual connection to each cell in the battery pack to monitor and manage statistical data and operating parameters of the cells. The latter involves a significant number of connections to highly precarious and dangerous power sources. This increases the probability of failure and fire significantly, especially if the BMS has not been correctly designed or attention given to the details of its installation and testing. With such many cables associated with these battery packs, costs are high, and manufacturers are constantly seeking solutions to lower these costs. Some experimental approaches may lower costs but may also result in increased fire risk. For example, using a small signal cable instead of a power cable for connections, not providing current limit on the sample lines, or only having one temperature sensor for large clusters of cells.

The BMS typically manages the cells centrally and reports to a high-level ECU regarding statistics and operations, as shown in Figure 3. If the communications link is compromised, the BMS is left on its own to manage the safety and expectations of the pack and is unable to share critical information such as temperature or flame detection under thermal runaway conditions.

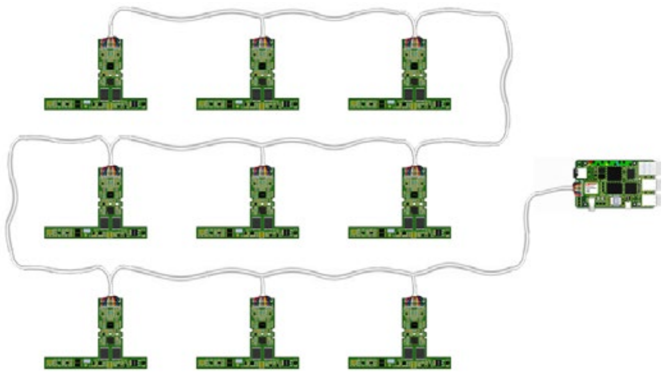


Figure 3 BMS with high voltage communications cabling connecting isolated cell managers together

Chargers should come with warnings attached to their cables and/or packaging that the products should not be used indoors, confined spaces or left unattended for extended periods, i.e., 3 hours, due to the potential risk of failure and resultant fires.

Consumers have responsibility to care for charging cables to ensure that batteries can be safely charged at all times. Where intermittent charging is observed or clear evidence of damage to the cable is noticeable, the cable should be discarded and replaced with a manufacturer specified cable.

2.2.3 Wireless BMS

As BMS evolve, wireless methods are becoming more widespread as they eliminate cabling, provide an internet-style mesh protocol network to allow multiple levels of communication, as shown in Figure 4. This configuration can guarantee damaged battery pack connectivity from the functional nodes is still operational, so the ECU can always manage a deteriorating pack. This allows authorised external parties (including fire brigades) to manage internal characteristics such as temperature and voltage to achieve a successful safe state for a fully compromised and dangerous battery pack.

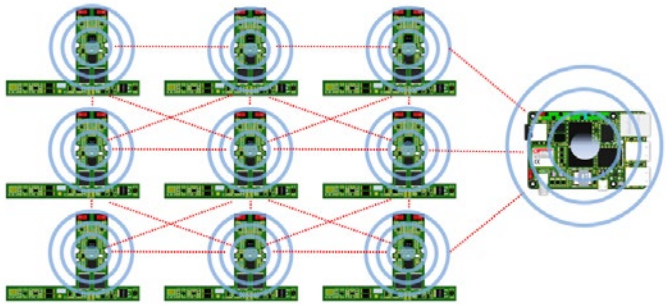


Figure 4 Wireless BMS, where all nodes can communicate to any authorised node or system

Wireless BMS systems offer greater safety over wired systems due to a significant number of improvements:

- A wireless BMS has reduced cabling and connections, making the system safer and simpler to manufacture and assemble.
- There is less risk of wiring strain and breakage, especially with vehicles where physical vibration and impact occur.
- The finished product is modular and scalable with simplified design; construction of an electric vehicle, with no need to design cable management paths and their testing regimes, reduces the number of components that could result in failure.
- Additional advantage of wireless BMS include reduced weight and therefore increased energy efficiency, the power to weight ratio performance is maximised, espeially benefical for transport applications.
- A wireless BMS can monitor battery packs continuously, and provide critical information to authorised parties during operation, maintenance, charging, fire management and risk analysis.
- Wireless BMS systems are compatible with factory and service automated assembly and testing processes.
- Repairs and replacements are significantly easier to manage, as modules can be swapped in/out safely in the field.
- Costs can be reduced significantly in design, manufacture, assembly, maintenance, and materials.
- With capability to operate autonomously or as part of a team (system), wireless BMS are highly receptive for re-use in second tier markets, with minimal physical connectivity problems.
- Key components within a wireless BMS (in the case of Texas Instruments) are declared to be ASIL-qualified (Automotive Safety Integrity Level) to D grade and ISO/SAE 21434 compliant (as with Analog Devices).

These advantages are associated with the battery pack and not the product. For example, if a battery pack is left on the dashboard of a vehicle where the temperature exceeds critical levels, the pack should be capable of utilising its integrated features to sound an alarm and flash a red LED to prevent a potentially dangerous situation, irrespective of the product. This would include the potential to send messages to interested parties authorised to interact with the product's battery system for warnings and status notifications. If the battery pack is installed in a product, it still has the capability to raise an alarm even if its host is turned off or damaged.

2.3 Thermal management in batteries

Battery packs managing many individual cells will generate heat from several sources that require monitoring and management. It is important for the pack's BMS to be aware of the system temperature to ensure safe operating conditions are met and maintained.

If a pack or its cells are subject to excessive heat, the following conditions may occur:

- **Excessive current draw.** Elevated temperatures can cause components to draw more current, which heats up the entire system.
- **Out-of-specification performance.** If components in the systems (such as semiconductors, capacitors, resistors) are out of specification, they may fail to regulate certain voltages (bandgap) and might report erroneous readings. Other components, such as switches or bus bars, may be subject to electronics impedance issues or resistance changes, meaning they are not operating correctly and may heat up, causing a potential fire hazard.
- **Cell thermal runaway**. If lithium cells are allowed to reach elevated temperatures (typically ~80°C and above) there is a risk of going into a self-heating cycle which cannot be halted. If this occurs, the cell may combust (the consequences of this are described in Section 3.1). It is critical to ensure lithium cells are kept within the stated operating temperature ranges for operating performance and consumer safety.

2.3.1 Sources of heat within a battery pack

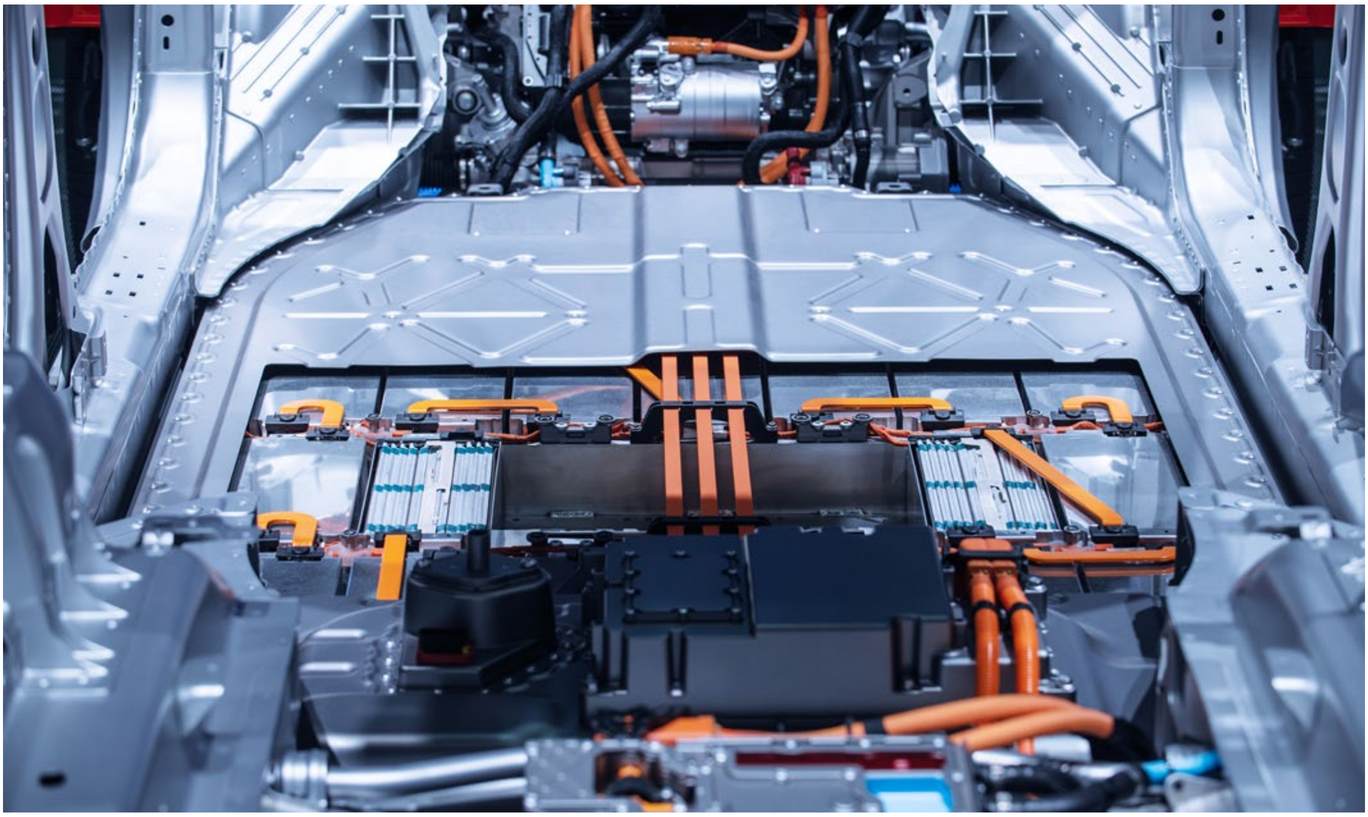
1. **Charging or discharging cells.** The process of power entering or leaving a cell has an associated thermal signature. Cells increase in temperature, due to Joule Heating, when they are either charging or discharging.
2. **Cell balancing.** When cells are having their voltage closely matched to other cells in the system for unity, it causes heat. A badly balanced pack, or cells that have aged and have a different charge/discharge footprint to the other cells, can result in a BMS system balancing cells constantly to ensure unity amongst the cells. The additional heat will require management to ensure safe operation.

3. **Semiconductors used for battery management.** Both switching and processing electronics produce some heat when operating. For processing systems, many BMS are designed to achieve lowest power use as most BMS are powered from the same cell(s) they are managing, thus heat dissipation is low. However, power semi-conductors used to control charge/discharge can produce a lot of heat when operating at full power.

Thermal management techniques ensure suitable operating temperatures. Most battery packs with active cooling, such as laptops, energy storage systems, and automobiles, utilize one of three common techniques:

1. **Forced air cooling.** Fans are a common method of cooling. Most fan-based cooling systems operate in such a way that, as the temperature of the pack increases, the BMS can request faster and increased airflow from the fan, providing suitable cooling with temperature-sensing feedback. Most fan systems have an integrated tachometer to allow underperforming or failed fans to be detected.
2. **Liquid cooling.** Used typically in larger, more modular and scalable systems, such as automotive. Cooled liquid from the host platform is piped into each individual battery pack system, where it is either injected through a heat-sink system to cool the pack and its cells or is directly injected into the enclosure (immersion) as a non-conductive (silicon or mineral oil) coolant to remove heat from all components. The BMS monitors the system temperature, can request a cooler environment if required, or sense and flag a temperature condition within the battery/device if the operating temperature is exceeded or not able to be managed.
3. **Hybrid forced air cooling with liquid radiator.** Fan cooling systems are now available with micro sized closed-circuit liquid-based radiators for enhanced cooling in small areas. With the maturity of radiator-based cooling systems (primarily driven by processor cooling technology) radiator systems provide the most cost effective and efficient cooling options.

It should be noted that many consumer products **do not have** active cooling as described here. Products such as Bluetooth speakers, mobile phones, thin tablet computers, power tools, e-scooters, and some e-bikes will not have active cooling systems. If consumers are unsure whether the device that they are purchasing has a cooling system, they should carefully check the product specifications.



2.4 Battery pack failures associated with no or underperforming BMS

The impact of having an underperforming or no BMS, is that cell failure is a significant risk. Table 4 lists some of the failure mechanisms that might occur and how these may be instigated.

Table 4 Common causes of battery pack failures associated with underperforming or no BMS

FAILURE CONDITION	CAUSE
Over temperature	Over-use - excessive charge/discharge cycles, or heavy loading
	Internal cell failures such as dendrites causing excessive current draw (thermal runaway)
	Inappropriate thermal management of battery balancing resistors
Over charging	Failure of BMS to prevent charge voltage from being applied **Example 1**
	Failure of charger to fold back or cease on completion of charge **Example 1**
Over discharging	Overuse- excessive or deep discharge cycles, or constant heavy loading
Manufacturer failures	Semiconductor leakage or internal insulation fault (short), **Example 2**
	Inappropriate separation of conductors resulting in breakdown (e.g., electrical peaks from charging)
	Moisture or water ingress to pack
	Choice of poor-quality components or cables, e.g., signal cabling instead of power cabling **Example 3**
	Inappropriate specification of printed circuit board (PCB) copper weighting
	Incorrectly specified semi-conductor power handling capacity
Environment	Exposure to aggressive weather conditions such as storms/hot weather/flooding
	Subject to enclosure fatigue, crushing or puncture (e.g., a vehicle accident) **Example 4**
	Long term use resulting in pack failure

In the subsequent section, we illustrate these modes and how they occur.

2.4.1 Examples of battery pack failure

In the following examples, several failure mechanisms that have been listed in Table 4 are described.

Example 1 Failure to cease charging (overcharge) results in gassing from reactions of the electrolyte with the electrodes (as described earlier), where pouch cells are most affected. In Figure 5 and Figure 6 unmonitored gassing causes packaging to expand and potentially rupture and release highly flammable gas, especially when vented under pressure.

Figure 5 NMC lithium pouch cells responding to overcharging, where (left) is the normal voltage conditions and (middle and right) are beyond the safe operating conditions

Figure 6 Tablet battery expansion when being charged by no brand charger is unable to manage its charge

Example 2 Cells in many products are packed together for space/density and are a key concern because the insulation provided is heat-shrunk and stretched. As the insulation is relatively thin the probability of an issue over time is high. Cylindrical cell insulation failures may result in short circuits of high currents between cells resulting in high temperatures and possibly fire.

The thin insulator material provided on these cells in Table 7 can be easily compromised by general wear and tear, allowing electrical shorts between any two of the 7000 cells in an EV to short and potentially flame.

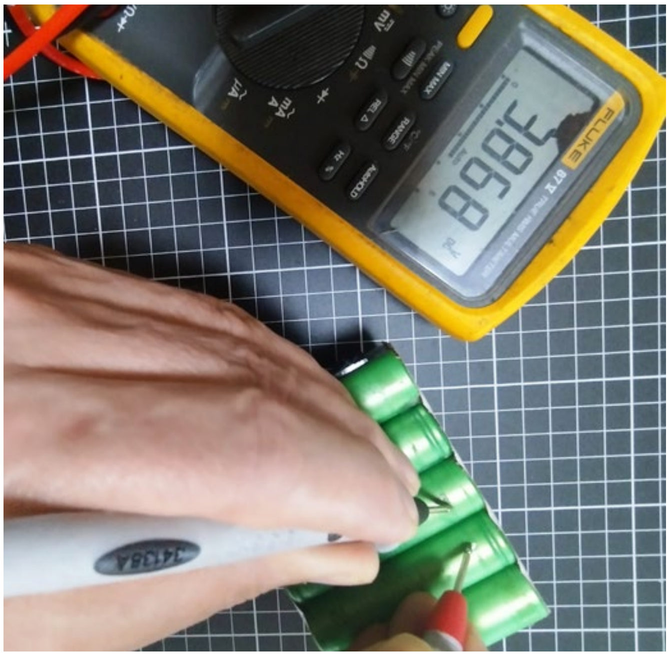


Figure 7 A cell's insulation is damaged through normal use and vibration over time and is subject to shorts; although the voltage is low, the current can be up to 40A, resulting in failure with probability of fire

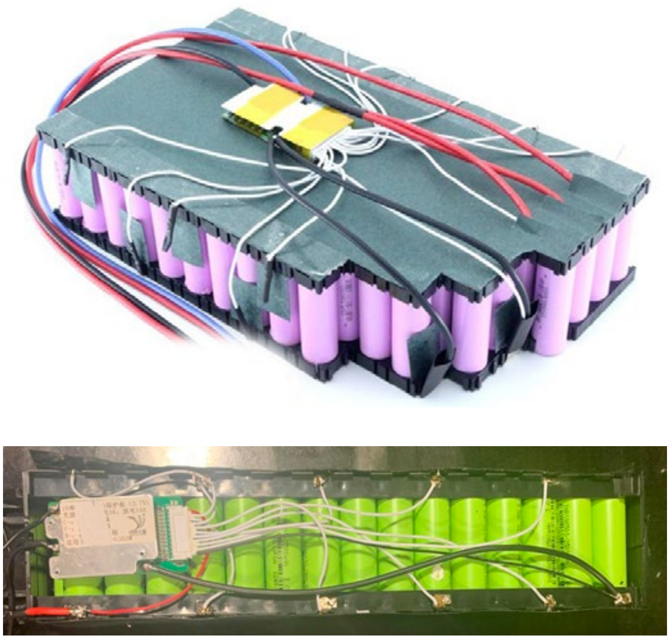


Figure 8 Example 3 shows the precarious cell balancing wiring that is unsuitable for e-mobility applications

Example 3 An e-scooter where, during assembly, lower testing and acceptance temperatures allow the product to pass factory quality assurance testing where cheap signal grade cable operates correctly as a battery balancing cable. However, if one of these many cables is pinched between two metal assemblies and/or subject to a high temperature day (i.e., left at the beach) the insulation material can be compromised, resulting in a catastrophic failure.

With the need to balance cells, the requirement to connect to each cell may result in some vendors using low cost, small cabling intended for signalling and not power applications. As a result, these small lightweight cables that are directly connected to high energy cells can cause failures when pinched, squashed, or compromised through impact or elevated temperatures.

If consumers recognise that a battery pack or device has been impacted either by an external force such as being dropped, lightning or other events, they should have the device inspected by the manufacturer or technician/electrician to ensure that all BMS components are operating correctly prior to charging.

Example 4 High energy cells (as shown in Figure 9) that can be damaged through general use must have appropriate BMS systems with appropriate sensors to detect failed cells, as their mode of failure typically results in a flame-ejection due to damaged structure, pouch exposure to the environment, and corrosion.

Figure 9 Damage to large high energy pouch cell due to impact at the corner

The BMS is designed to prevent these conditions and be able to respond quickly by providing notification of a compromising situation, to either the application and/or the users. The BMS can remove power, prevent power from leaving the pack, or request accelerated cooling, but if these actions cannot produce a result, it can provide a priority notification that it is compromised. It acts as the gatekeeper and first line of defence for catastrophic failures in lithium battery packs. The BMS can identify shorts occurring because of the change in voltage among other sensors, and can limit the possibility of fire, save lives, and reduce asset damage.

2.5 Future BMS solutions

Future Battery Management Systems will be manufactured small enough to be placed inside the cell itself.
This could potentially enable better fire prevention.
With technology advancements in smaller semi-conductor devices, the BMS can be realised as an extremely small module, allowing the manufacturer to embed control into their product, which will ensure that their cells will always be used within their specifications.

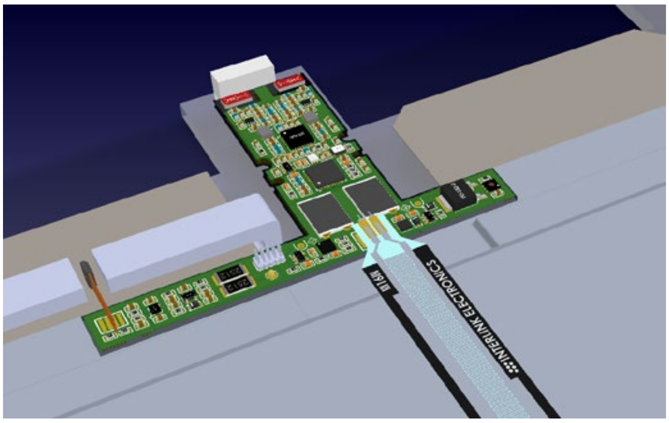


Figure 10 A wireless micro-sized BMS integrated into the cell, monitoring all conditions as an 'excellent' grade BMS

A potential future benefit of wireless BMS systems is that they can communicate directly to emergency services to assist in incident management, characterise the damaged cells/battery pack and confirm their fire status, allowing a damaged vehicle to be thoroughly extinguished, transported and monitored safely.

2.6 Lithium-ion battery chargers

Chargers play a significant role in the performance and reliability of battery-based systems by providing an appropriate energy potential throughout the charging process to charge the cells. In some instances, the charger may be required to play the role of the BMS when charging the battery, i.e., for small consumer items or products charged from a USB device.
The conditions and requirements for safe charging vary considerably when the process is underway.
The requirements and variables are monitored and fed back into the charge algorithms, which are driven by the BMS statistics and environmental conditions.

> Original Equipment Manufacturers (OEMs) should provide accessible consumer advice (e.g., websites, help files on devices, instruction manuals, or other paper documentation) inside products stating to always use chargers and cables sold for/with the products rather than using generic chargers and cables.

A typical BMS will manage the charging process by utilising sensors to gauge the current operating conditions and provide feedback to the charger regarding which algorithm or phase of an algorithm is required at that time. Communication with the charger or the ability to fully control the charge is a critical requirement for safe charging.

2.6.1 Typical charging method

Software updates from suppliers can recognise whether their device is charging with OEM product(s). If the device is charging with a non-OEM product it may inform the consumer and issue a warning, via the interface, requesting user to acknowledge that the device is being charged with a generic charger and/or cable and that damage and/or failure could potentially occur for the device i.e., phone, laptop, or another interface device.

Figure 11 illustrates the charging phases associated with a lithium-ion battery

1st Phase: Cell signature detect, trickle charge, linearity sense. This phase provides a small current to monitor the cell behaviour, confirm all cells are performing as expected, excite the chemistry ready for bulk charge and confirm the linear charge rate, verifying the cell array is in balance.

2nd Phase: Bulk Charge – high current transfer. Starting at 1ºC while monitoring all conditions for correct charging up to 10ºC (current equivalent to 10 times the Ah of the battery pack if measured in Amps), the charger starts the Bulk Charge phase of the charging process utilising synchronous rectifiers and high frequency pulse width modulation for high efficiency and low heat to transfer AC energy from the grid to DC power into the battery pack.

This process is tightly aligned with the BMS operating parameters for confirmation of safety and correct operating conditions whilst the energy is transferred into the cells.

3rd Phase: Top close off charge. As the battery pack becomes fully charged, the balancing circuits will start to operate to move excess energy across the pack to cells that need it most, preventing other cells which are now charged from over-charging. As the pack reaches unity with all cells reaching the same charged voltage, the BMS notifies the charger to cease providing power.

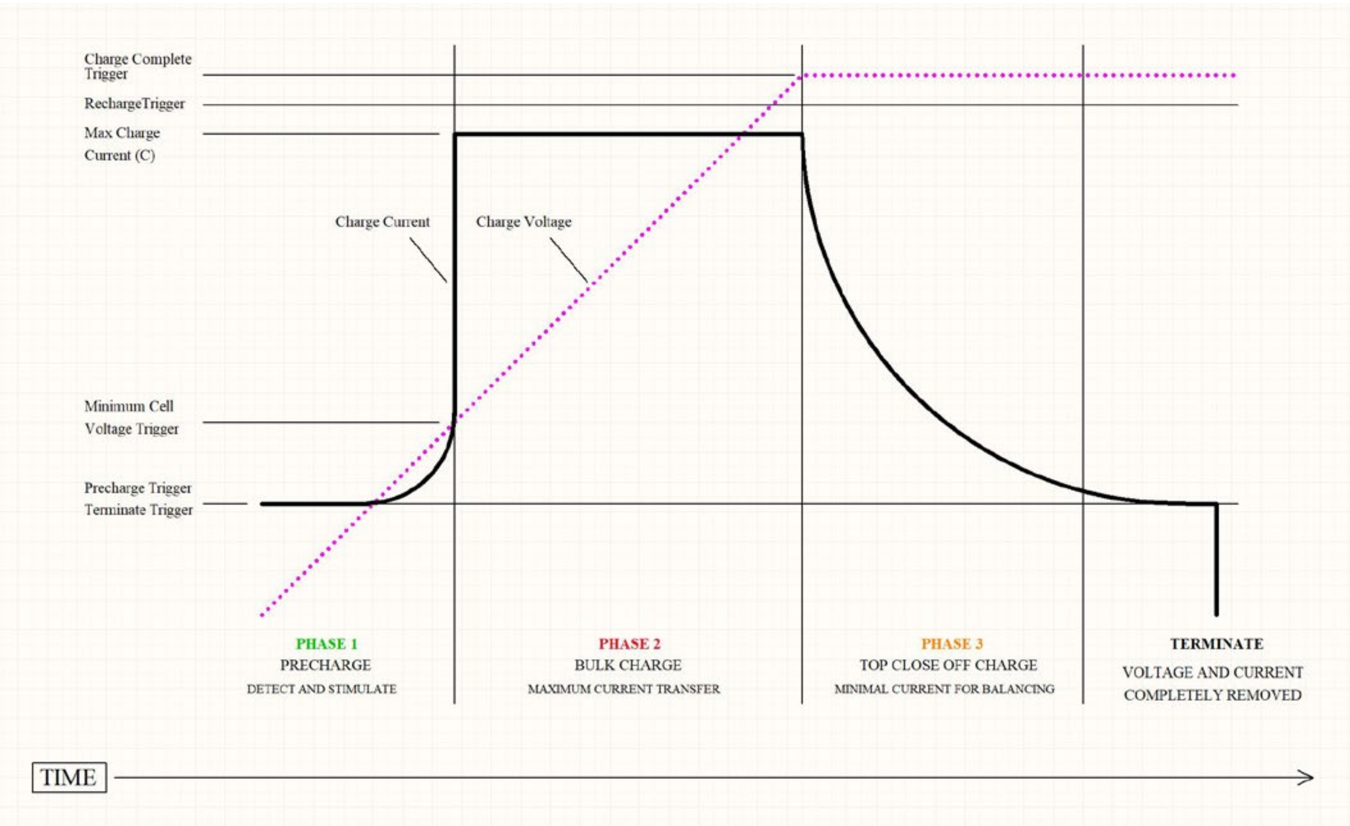


Figure 11 Charging method for a lithium-ion battery and the associated charging phases

As the charging process is executed, there are many sensors connected to the BMS which are monitoring the conditions of the pack. Examples of some conditions together with the associated risks that need to be monitored and considered are:

1. **Low voltage**. A cell with a voltage that is too low is a high-risk situation and requires the charger to perform a preventative low trickle charge, attempting to bring all cells up to the same minimal voltage in preparation for the next phase, which is 'bulk' charge. A cell that is damaged by being under voltage runs the risk of catastrophic failure during the bulk charge phase and is a potential fire hazard.
2. **Temperature.** Higher cell/pack temperatures will result in the charger being requested to provide a much lower (to zero) charge rate to keep the cell/pack temperatures low. Cells that are too hot risk a catastrophic failure during bulk charge.
3. **Gassing.** Cells that are sensed as gassing will result in a low trickle to zero charge. If gas is sensed or a force sense resistor detects pouch expansion, the charger will limit its charge to a trickle until the fault is cleared, or it times out and notifies the host that a pack failure has occurred. Bulk charging gassing cells can result in catastrophic failure.
4. **Over current.** If the pack experiences over current in any cell or group, a failure may have occurred in that cell and the charger will 'fold back', restricting the current according to its algorithm. If the BMS determines that the current draw on a particular cell/group is a fault condition, the BMS will instruct the charging process to cease, and a fault will be flagged to prevent catastrophic failure.
5. **Arc/flashover.** Usually detected during bulk charge; if an arc or flashover is detected, the BMS will instruct the charger to cease immediately and flag a priority fault to the host.
6. **Humidity**. Moisture makes the air more conductive. Humidity will change the charger's algorithm to attempt to charge under safe conditions. If humidity is high, a trickle charge will be offered. However, if it is excessive, the charge process will cease completely to prevent risk of potential failure due to electrical flashover/shorting of components and resulting fire risk.
7. **Impact/vibration**. If the battery/cell environment is subject to impact or excessive vibration during charge, the BMS will notify the charger to cease. With cells relying on good contact for charging and monitoring, significant vibration/impact can cause temporary disconnection to occur, causing flashover and potential damage to connectors and corrupted sensor and data communications.
8. **Pressure**. If the ambient pressure has changed, the BMS may notify the charger to cease, as a potential battery casing breach may have occurred, opening the pack to the outside environment and no longer under controlled conditions (such as a rock puncturing the battery housing, a tear on the battery housing or penetration).
9. **Earth leakage.** If a pack experiences earth leakage (a cell has shorted to the chassis), the BMS will request the charger to shut off the charging process immediately to reduce the risk of a live chassis and shock hazard.

Although many low-cost chargers have specifications that may match the application, requirements such as full disconnect on charge, current limit when hot, or hot plug compliant connection (no output until device connected) can introduce the risk of compromising the BMS, resulting in a potential risk of catastrophic failure and uncontrolled release of the cell's energy.

2.6.2 Areas of common charger failure

Common failure mechanisms of chargers in combination with the BMS include:

1. **Failure to remove charge potential.** Not using appropriately rated devices or semiconductors where the charger can fail in the 'on' state, damaging the device being charged.
2. **High leakage.** If the charger is not powered when plugged into the device under charge, it may then leak power from the device being charged back to the charger, causing the cells to drain and suffer damage due to under-voltage (i.e., during a household power failure).
3. **High peak voltages.** If a device is connected to a charger that is powered on, a high voltage spike due to instantaneous connection may be inflicted on the device being charged as it is being plugged in. This voltage spike can damage the input protection of the BMS circuits and cause the device to fail or charge in an uncontrolled fashion, causing destruction.
4. **Low quality protection circuits.** This may occur if a Positive Temperature Co-efficient (PTC) instead of a direct current (DC) fuse is used. A DC fuse will blow and 'go open', protecting the device being charged. However, PTC fuses require a circuit to be maintained to keep the PTC in the high-resistance state; this leakage voltage can cause the device charging to be over-charged from trickle-charging.
5. **Y-class capacitor spiking**. Common circuits that are used to obtain compliance with radio frequency (RF) emission standards (Y-class capacitors) can compromise the safety circuits of a charger. In the event a figure eight AC power cable is used with the charger, a capacitor can be connected to 'active' and cause AC power spikes at connection time, damaging the device under charge and potentially resulting in uncontrolled over-charging.
6. **ESD/lightning.** For consumer products with little to no Electrostatic Discharge (ESD) protection, normal human activity that generates ESD can compromise and cause uncontrolled charging conditions. For mobile platforms such as EVs, understanding the effects of lightning is still crucial, as this is a common phenomenon that is detrimental to integrated circuits and may cause corruption and damage to the BMS operation.

At present, it is uncommon to purchase generic charging devices, however, the passing of 'right to repair' laws,[7] which have been enacted in Europe, and the resultant development of universal connector standards, including, in one example, the move from Lightning connectors to USB C connectors, may open a flood of generic, cheap chargers that are not made with high quality components. As a consequence, should Australia enact similar laws, consumers may end up purchasing cheaper, poor-quality chargers that may cause a spate of significant problems.

Develop a star rating for all charging products, to inform consumers about the quality of the product that they are purchasing. Standards bodies and regulators should consider a rating system on a scale of 1 to 5 for respective charger controls and managements systems.

Issues relating to the use of home electric vehicle chargers and implications for home safety have not been considered in this report.

There are many variables related to the age of a home, the electrical wiring within it, the position of the charging point of the car, charging point to be either fixed or standalone, 10 Amp or 15 Amp General - Power Outlets (GPO). This may be the subject of a further report for standards and regulatory bodies to consider.

7 Right to repair: Making repair easier for consumers (europa.eu)

3 Failure of lithium-ion batteries

3.1 Hazards of lithium-ion battery failures

Lithium-ion batteries are susceptible to thermal runaway under abuse conditions, leading production of gases as described in the earlier sections. In most instances, these are very violent events and the gases emitted are flammable and toxic. The fire hazard is due to the combustible system components, battery chemistry and format, electrical capacity, and energy density. Materials of construction, design of components, and the BMS can also contribute to the hazard.

3.1.1 Off gassing and smoke

Gases are generated when the overheating and thermal runaway process in a lithium-ion battery occurs, as described in Section 1.1. When a battery ruptures, gases and/or smoke are released that are hazardous to health in the same way that smoke is from all fires. Carbon monoxide (CO) is the main toxicant in accidental fires that can lead to health impacts and, potentially, death. Smoke from burning lithium-ion batteries also contains many other toxic and irritant chemicals, such as hydrogen cyanide (HCN), acrolein, polyaromatic hydrocarbons (PAH), and volatile organic compounds (VOCs). Hydrofluoric acid (HF), an extremely corrosive acid and dangerous chemical, is also likely to be present in lithium-ion battery fires due to the presence of fluorine within the electrolyte. Thick smoke can obscure visibility, preventing occupants from finding an exit to move away from the fire.

Where a consumer determines that the lithium-ion battery is venting gas or sees smoke coming from a battery, they should immediately move away to a safe space. Inhalation of gas and/or smoke should be avoided to prevent potentially harmful health impacts. This is evidenced by NMC- and NCA-based lithium-ion battery fires reportedly causing health problems for fire fighters because of the cobalt and other particulates,[8] poisoning those breathing in the smoke. The liquid and solid residues created during a fire are toxic and corrosive, and care should be taken to prevent physical contact.

HF requires specific treatment, in addition to irrigation with water (which is typical to treat acid burns), consumers **should immediately seek emergency hospital treatment**.[9]

To prevent these events from occurring, consumers should ensure that they are using the correct charger for their devices, the charging cable is in good condition, that the batteries are not showing evidence of bulging cells or distortion of the device/product, the device/battery is not excessively hot prior to or after commencing charging, nor is it 'hissing', which indicates venting. If any of these conditions are observed, the consumer should remove the battery from service (if safe to do so), place in fire resistant container (e.g., metal drum) with sand or other extinguishing agent, and dispose in accordance with local, state, and federal regulations. To find a local battery recycling agent for disposal instructions, the Australian Battery Recycling Initiative[10] (ABRI) can assist.

In the event of battery off-gassing, smoke or fire in a confined space, move to safety and call Triple Zero (000) to alert authorities of the fire. Where possible, callers should also clearly state it is a battery fire and identify the item type.

If a person(s) does inhale lithium-ion battery vent gases or smoke or has physical contact with liquids or solid products from the fire, they should immediately report to a hospital emergency department for treatment.

8 Experimental determination of metals generated during the thermal failure of lithium ion batteries - Energy Advances (RSC Publishing) DOI:10.1039/D2YA00279E

9 CDC | Facts About Hydrogen Fluoride (Hydrofluoric Acid)

10 Association for the Battery Recycling Industry

3.1.2 Fire

Smoke and gases produced during thermal runaway events of lithium-ion batteries are flammable and can ignite and burn. The potential of this will depend on a heat/ignition source being present, access of air, and containment of the cell. Depending on the design of the device and proximity to other items, this can lead to ignition of the other components, such as the electrical device that the battery is in or adjacent combustibles (wiring, other components) and potentially spread fire throughout the enclosure, building, or vehicle.

Figure 12 Bluetooth speaker where the embedded battery has caught fire (supplied)

Lithium-ion battery fires are complex and there are very few effective means to extinguish them quickly and safely. Fire and Rescue NSW (NSWFR) offers practical advice for fighting small fires from consumer devices.[11] For smaller consumer batteries, it is ideal to use a foam extinguisher, CO_2, ABC dry chemical, powdered graphite, copper powder or soda (sodium carbonate) as you would extinguish other combustible fires, **if it is safe to do so**.

For larger batteries, such as those in ESS and EVs, containment of the fire may be difficult because of the high temperatures and volume of material, so copious quantities of water will be needed to reduce the intensity of the fire. **It is recommended that in event of these fires, call Triple Zero (000) for immediate assistance.** FRNSW offers additional advice.[12,13]

It is not recommended that untrained persons fight battery fires, especially if they are in confined spaces, due to the risk of significant injury.

Where it is possible to fight a small battery fire, use a foam extinguisher such as CO_2, ABC dry chemical, powdered graphite, copper powder or soda (sodium carbonate) as you would extinguish other combustible fires. Call Triple Zero (000) to inform of the fire.

3.1.3 Explosion

The smoke and gases produced during the thermal runaway event of a lithium-ion battery, if not ignited, may collect in a quantity and mixture that may create an explosive atmosphere. The potential of this will depend on a heat/ignition source being present, access of air, containment, etc. Explosions can be categorised as *deflagrations*, where rapid flash fire occurs. If the gases are contained, a greater pressure wave or build up can occur which is a much more damaging *detonation*. Both events can potentially cause significant injury or damage to people and property.

3.1.4 Implications of use and location

The location or occupancy type of an off-gassing, smoke, fire and/or explosion event will have implications on the severity of the outcomes. Smaller electrical devices such as laptops, mobile phones, Bluetooth speakers and power tools will be charged inside and fire, whilst potentially small, could quickly spread in such an environment. To mitigate this, it is recommended that devices are charged on surfaces that will not combust in the event of fire and cause the fire to potentially spread further.

11 What should I do if my device or battery is smoking or on fire? - Fire and Rescue NSW

12 https://www.fire.nsw.gov.au/page.php?id=9391

13 https://www.fire.nsw.gov.au/page.php?id=9390

Batteries should be charged on non-combustible surfaces and away from combustible items.

Electric scooters or bicycles are more likely to be outdoors or in storage areas, however, whereas mobility scooter fires have a higher chance of occurring in an aged care facility or house where the occupants have limited mobility, impacting the likelihood of evacuation from the event. It is recommended that these devices are stored on non-combustible surfaces, in a cool, dry place and not prone to direct or excessive sunlight that can cause the battery pack/device to potentially overheat. The frequency of fire incidents is increasing. The US Consumer Product Safety Commission reported that micromobility-related fires had resulted in at least 19 fatalities in the USA in 2021/22. In New York City, fires caused by batteries that power 'micromobility devices' grew from 44 in 2020 to 220 in 2022 leading to possible new legislation and the release of the Action Plan.[14] Temporary bans of e-scooters on public transport have been enacted in some jurisdictions.[15,16]

For home battery systems, AS NZS 5139:2019 specifies requirements for general installation and safety requirements at the scale typical for homes. Further, an additional guide has been developed by the Clean Energy Council, with the support of several other partners, for the installation of these home and larger energy storage systems.[17]

3.1.5 Automotive

Electric vehicle availability and sales are increasing exponentially in the Australian market. The Electric Vehicle Council reported sales of 26,356 electric vehicles to September in 2022.[18] Whilst there will be more electric vehicles on the road in the coming years, fires are rare when considering the frequency compared to other products, specifically internal combustion engines. Most consumer concern about EV fires relate to the size and intensity of the fire and the challenge of effectively extinguishing them.

However, when an EV is involved in an incident where the battery is compromised by crush, puncture, or fire (such as a housefire in a garage) the potential of a significant incident is heightened.

If the vehicle is in an underground carpark, apartment block or house garage, this can increase the potential consequence of the size and scale of fires associated with failure. An electric vehicle battery is big (in size, voltage, and electrical capacity) and therefore holds a significant amount of energy. The consequent inherent risk is proportional to the size of the battery. Various research projects concerning EV fires are under currently underway, such as Safety of Alternative and Renewable Energy Technologies (SARET).[19]

In the event of a fire, emergency responders are reporting extinguishment of vehicle fires to be exceedingly difficult. Reports suggest that up to 150,000 litres of water are required to extinguish a battery fire.[20] Additionally, due to the chemistry of a lithium-ion battery, there is risk of re-ignition of the fire.

Never fight an EV fire. Call Triple Zero (000), state the make and model of the vehicle and move away to a safe zone, away from smoke.

14 https://www.nyc.gov/assets/home/downloads/pdf/office-of-the-mayor/2023/micromobility-action-plan.pdf?utm_medium=email&utm_name=&utm_source=govdelivery

15 https://tfl.gov.uk/info-for/media/press-releases/2021/december/tfl-announces-safety-ban-of-e-scooters-on-transport-network

16 https://www.atm.cat/ca/w/np_?p_l_back_url=%2Fca%2Fcomunicacio%2Fsala-de-premsa%2Fnotes-de-premsa

17 Battery Safety Guide – Battery Safety Guide

18 https://electricvehiclecouncil.com.au/wp-content/uploads/2022/10/State-of-EVs-October-2022.pdf

19 Safety of Alternative and Renewable Energy Technologies (SARET) Research Program - Fire and Rescue NSW

20 Up to 150 000 liters of water needed to put out a fire in an electric car | CTIF - International Association of Fire Services for Safer Citizens through Skilled Firefighters

The United States Transportation and Safety Board (NTSB) has completed a safety report on electric vehicle fires and the implications for first responders, which they have illustrated with case studies.[21] The authors made ten findings regarding safety concerns for first responders at electric vehicle fires, amongst them:

- concerns that crash damage and resulting fires may prevent first responders from accessing high voltage disconnects, presenting a risk of electrocution
- that most manufacturers' emergency response guides for fighting high voltage lithium-ion battery fires lack vehicle-specific details (at the time of writing)
- thermal runaway and multiple battery reignitions after initial fire suppression are safety risks in high voltage lithium-ion fires.

The dangers of battery fires have been highlighted earlier in this report. Emergency services of several Australian states are endeavouring to identify best practice for dealing with EV fires. Information on the make, model and year of a vehicle are useful to share with the fire service in assisting to manage a fire.

3.1.6 Storage of unused batteries

Unused batteries or batteries that are not being regularly used should be stored in a cool, dry place away from excess heat or ignition sources and never in a fully charged state. As noted in the earlier section, batteries that use LCO, NMC, or NCA type cathodes are in their most unstable state when fully charged. However, it is unsafe to store batteries in a fully discharged state as well. Lithium-ion batteries are recommended to be shipped and/or stored at 30% SoC to ensure that they are in the safest state possible as referenced IEC 62281[22] (batteries). A consumer can determine the SoC of a battery either by an interface which will provide this information or a series of LEDs that will provide indicative levels of charge of the battery.

3.1.7 Modifications or enhancements of batteries and cells

In recent times, there has been a surge in the modification of lithium-ion batteries to either increase the voltage or the capacity of the battery pack. In some instances, multiple battery packs are wired together in either series or parallel to increase the voltage or capacity of the pack.

> Consumers should not modify products with larger or additional batteries due to risk of significant catastrophic failure. Products should be used in strict accordance with manufacturer guidelines and operating instructions.

3.1.8 Research into battery fires

Research into the fire safety systems such as building fire detection, suppression or fire control with sprinklers and adequate separation distances is being carried out around the world. There are several commercial gas detection systems that can be connected to the BMS as a method to externally sense when gassing events occur and shut down the battery. These solutions are typically suited to larger energy storage systems. Internal sprinklers can prevent or delay fire spread.[23] Suppression techniques for electric vehicles are being investigated in Europe.[24] Fire and Rescue NSW are also currently conducting the SARET research program.[25]

21 National Transportation Safety Board. 2020. Safety Risks to Emergency Responders from Lithium-Ion Battery Fires in Electric Vehicles. Safety Report NTSB/SR-20/01. Washington, DC.

22 IEC 62281 *Safety of primary and secondary lithium cells and batteries during transport*

23 https://www.fmglobal.com/insights-and-impacts/2020/energy-storage-systems

24 https://brandogsikring.dk/en/news/2022/new-knowledge-about-battery-fires-in-electric-cars-on-ferries/

25 Safety of Alternative and Renewable Energy Technologies (SARET) Research Program - Fire and Rescue NSW

4 End of life considerations for lithium-ion batteries

4.1 Second life batteries

Second life batteries are aimed at the energy storage systems (ESS) market using EV batteries that still have 80% of the initial usable capacity. Re-use can provide value in markets where there is demand for batteries that require less frequent cycling. They are also considered to be a cheaper and potentially more available alternative to a brand-new battery pack especially when considering the current cost and demand for new batteries.

A second life battery pack consists of modules and/or full packs taken from an EV and then 're-manufactured' into a new battery pack. Depending on the company undertaking the build, the steps undertaken include determining the SoH of the modules/battery, addition of a new BMS suited to the ESS application, addition of cooling systems, addition of new electrical connections between modules and an inverter for external connection. A key part of this work is the determination of SoH of the EV packs to ensure that the cells within it are in good working condition and suitable for on-going use and do not pose a hazard in their subsequent application.

As detailed earlier, the BMS on EVs have many sensors on the cell/modules to determine the SoH of the battery pack. This includes registering incidents of shock and vibration, i.e., an accident, or where the pack has been exposed to extreme temperatures (either hot or cold) for extended periods of time. Battery packs that have been subjected to a significant number of high temperature events, shock and vibration, should be sent to recycling rather than be re-purposed.

> Methods and approaches for the disposal of damaged batteries are developed to inform how a battery should be handled at EOL. At present, there are no readily available methods and sources of information that the public can adopt to allow them to safely manage a damaged battery and places for appropriate disposal/recycling. There is an urgent need to address this problem.

It is likely that companies using batteries in second life applications within their businesses and do not sell the packs to second or third parties will have significantly greater insight into the first life history of the pack and will accept the risks that come with second life uses. However, consumers who are purchasing second life battery packs that have come from EVs or other first life applications should know the history of the batteries within the pack through open interrogation of the BMS so they understand the potential risks of purchasing a second life battery.

As this is a relatively new market there are no second-life-battery standards which the authors are aware of. No guarantees exist regarding second-life-battery quality or performance, and few industry standards focus on BMS or SoH disclosures, let alone standard performance specifications for a battery that is to be used for a given application.

4.1.1 Sale of second hand EVs

The second-hand market for EVs will substantially increase in the years ahead due to the proposed stimulus for EV sales in Australia. It will be important to ensure that consumers have as much information about the state of health (SoH) of an EV battery pack when making a purchasing decision as the cost of battery replacements are substantial. The easiest way for a consumer to understand the SoH of the battery is to ensure that the BMS allows for as much information to be made available so they can make an informed decision about purchase. At present many BMS systems are proprietary to the OEM and there is limited information made available that can be accessed and understood in a meaningful fashion. Regulators may need to intervene to define what information is to be made available from an EV BMS for consumers to be more informed about the SoH of a battery within a vehicle.

4.2 Collection and recycling of batteries

Recycling of lithium-ion batteries is an important step for the EOL management and to minimise battery disposal hazards and environmentally harmful waste. At this time, battery recycling rates in Australia are reported to be extremely low[26] and there is an urgent need to enhance collection rates to capture the embedded value of the materials that remain in a battery at EOL, minimise hazardous waste and fire risks to users and the public associated with incorrect disposal.

26 Australian landscape for lithium ion battery recycling and reuse in 2020 (fbicrc.com.au)

E-bikes, e-scooters, hoverboards and other small transportation batteries should be banned from second life applications and should be sent directly to recycling. Further, consumers should avoid purchasing these second-hand items due to a lack of information around the SoH of these batteries. Where it is possible to purchase a replacement OEM battery for the product, for example an e-bike, they should replace the battery for safety and dispose of the old battery via a recycling centre as appropriate.

Battery disposal collection points need both standards and regulation to define the minimum requirement for safe collection, storage, and transport to recycling depots. Current collections occur in public places and stores which can pose a hazard to people and property in the event of fire. There should be national standards and regulations to manage these issues.

Collection issues for EOL lithium-ion batteries are significant, especially for smaller consumer batteries, and need to be addressed with uniform national standards. Currently each state has very different standards. Harmonisation would assist in collection and recycling rates and minimise safety hazards especially for damaged batteries. Collection sites should have separate boxes for either damaged/faulty batteries and exhausted/visually intact batteries that will reduce the risk of significant fires from damaged/failed batteries during the collection process. Further, where possible, the terminals of the battery pack should have tape applied to electrically isolate the terminals and prevent inadvertent short-circuit of the cells in the collection bins during storage and transportation.

Disposal of batteries in household rubbish is a significant risk due to the batteries being intermingled with liquids and solids that could cause the battery to fail within the bin. Further, on collection of household rubbish, the battery can be potentially crushed in the garbage truck leading to a significant fire risk. Although batteries, in many instances, have markings indicating that they should not be put in a (household) bin, a public education campaign may be required to emphasise this message and increase recycling rates.

No batteries (especially damaged or EOL) should be disposed into household rubbish, due to the risk of fire in household rubbish bins and garbage collection trucks. Batteries, which are intact, should be disposed of at a recycling station.

Lastly, there is an immature regulatory regime for battery recycling. Today, while most international markets have some form of regulation requiring the recycling or remanufacturing of consumer electronics in general, most markets do not have EV-battery-specific requirements or delineations of responsibility between the producer and the consumer. It is noted that the Australian Government has supported the Battery Stewardship Council,[27] however, the lack of regulation creates uncertainties for OEMs, second-life-battery companies, recyclers and potential customers. The lack of regulation also gives rise challenges to battery recycling for EOL lithium-ion batteries and leads to low collection rates, environmental pollution due to poor disposal practices and hazards to the public.

27 www.bsc.org.au

5 Standards for lithium-ion batteries

5.1 Standards and regulations

Many national and international standards have been published to address risks that lithium-ion batteries may present to end-users. Standards are published by numerous bodies around the world, including the International Organisation for Standardisation (ISO) based in Geneva, Switzerland. Committees write ISO standards to cover a vast array of areas, applications, industries, products, systems, etc. ISO standards are often adopted directly for regulation in Australia or elsewhere, or sometimes adopted and modified as local standards. There are national standards bodies in many other countries, such as the Japanese Standards Association, which publishes Japanese Industrial Standards (JIS), and the American National Standards Institute (ANSI).

In Australia, the peak standards writing body is Standards Australia, which develops standards written by committees of members of nominating organisations and adopts[28] standards written by overseas bodies.

An important standards development body in the field of lithium-ion batteries is the International Electrotechnical Commission (IEC). The IEC defines itself as an organisation '*whose work underpins quality infrastructure and international trade in electrical and electronic goods*'. Similar to ISO standards, IEC standards are referenced directly within other standards or local regulation, and are sometimes adopted with local modifications (e.g., to form an 'AS IEC' standard).

Standards relevant to lithium-ion batteries are also developed and published by organisations with longstanding activities related to electrical and fire safety, such as Underwriters Laboratories (UL) headquartered in Northbrook, Illinois, USA.

The relationship between the various standards published by the organisations mentioned above and others is complex. Often, one standard will reference many other standards. This approach is intended to standardise test methods across many fields of application, but this results in specified requirements or conditions being spread across numerous referenced documents. Additionally, regulations in any region or country can reference standards written by any combination of standards development organisations if they are seen to be appropriate for the purposes that the regulations are attempting to fulfil.

Each standard is typically limited to a specific scope. This ensures that it is relevant to the application or use that the original authors considered during its development.

Existing standards that have been published to address lithium-ion batteries may be generally categorized as either performance or safety standards. Some published standards include aspects of both.

5.1.1 Performance standards

Performance standards intend to provide a standardized method for determining whether the battery operates in the way claimed by the manufacturer. This may include tests on storage capacity and charging and discharging rates. These standards are important as they permit a manufacturer to integrate a battery into a product to ensure that they are selecting one with adequate performance for the intended application.

28 Either with modifications to tailor the standard to Australian conditions, or without further modification.

5.1.2 Safety standards

Safety standards address the risks presented to the user due to reasonably expected conditions during a cell or battery's service life. These standards typically contain so-called abuse test methods. SAE J2464[29] defines abuse testing as that which:

… is performed to characterize the response of a rechargeable energy storage system (RESS) to off-normal conditions or environments. The primary purpose of abuse testing is to gather response information to external/internal inputs that are designed to simulate actual use and abuse conditions.

The abuse tests may be designed to apply to individual cells or batteries, or systems of batteries and associated and/or included charging and management components (i.e., BMS).

Test regimes may be grouped as follows:

- Environmental: altitude (low pressure), thermal (exposure to high and low temperatures), and thermal shock/temperature cycling.
- Electrical tests: external or internal short-circuit, abnormal charge (overcharge), forced discharge, continuous low-level charging, and reverse charge.
- Mechanical tests: vibration, shock, impact, crush, drop, projectile, penetration.

Each standard provides specific criteria to assess successful response to the applied test. For example, the IEC series of standards listed below identify the following characteristics as evidence of failure of a battery to withstand the applied tests: deformation, venting, leakage, smoke, rupture, fire, or explosion.

Many standards have aspects of testing related to both performance and safety.

5.1.3 Products

There are many standards related to specific product types or categories. This type of standard is commonly adopted for national safety regulation. Various classes of consumer product standard and regulations are provided in Table 5.

In addition to detailing specific requirements and tests, many product safety standards refer to battery safety standards. For example, AS IEC 62368.1, which national electrical safety regulations via the Electrical Equipment Safety System[30] require mandatory compliance for audio/visual, telecommunication and business equipment, references IEC 62133-2 to establish the safety of included lithium batteries.

Road vehicles are required to meet the Australian Design Rules (ADRs) in accordance with the Motor Vehicles Standards Act 1989. The recently published draft of ADR109/00 *Electric Power Train Safety Requirements*, related to Class M (passenger vehicles) and N (goods vehicles < 3.5 t, e.g., van or ute). ADRs are performance-based, and draft ADR109/00 draws from, and directly recognises as being equivalent to UN100/R03 and includes specific performance and abuse tests performed on the vehicle itself but does not mandate the use of batteries complying with any particular standard.

As nominated explicitly in SAE J2464, the tests described by many of the standards listed in Table 5 may be conducted on cells, batteries, or products without active protection mechanisms. Taking this approach can provide a method to determine safety levels and integrity levels required for functional safety analysis.

29 SAE J2464, Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing.

30 https://www.eess.gov.au/about/about-the-eess/

Table 5 Battery and product standards for a range of applications. Note – this table should not be considered exclusive or fully complete as many application areas exist that make use of Li battery-containing products

APPLICATION/AREA	CAPACITY RANGE (WH, APPROX)	RELEVANT STANDARD(S) AND PRODUCT/APPLICATION TYPE	REGULATORY UPTAKE (IF ANY)
Non-rechargeable (primary) button/coin batteries	< 5	IEC 60084-4[31] (batteries)	**Consumer Goods (Products Containing Button/ Coin Batteries) Safety Standard 2020** Mandatory compliance to ACCC standards, regulated through Commonwealth legislation.
Portable electronic devices, including cell phones, laptops, tablets, and other devices, toys, Electric scooters	5 – 100	IEC 62133-2[32] (batteries) UL 1642[33] (batteries) JIS C 8714[34] (batteries) UL 2054[35] (batteries) ANSI C18.5[36] (batteries)	Electrical safety regulations, IEC 62133-2 via IEC 62368.1
Audio/video, information and communication technology equipment, business, and office equipment.	100 – 1000	(AS) IEC 62619[37] (batteries)	Electrical safety regulations, IEC 62619 via IEC 62368.1
Industrial and Household storage	1,000 – 15,000	IEC 61427[38] (renewable applications) AS/NZS 5139[39] (energy storage systems) UL 9540[40]/UL 9540A[41] (energy storage systems)	NSW building regulations specify AS/NZS 5139 (through AS 3000 as a state variation to the NCC).
Motive (non-road vehicles) Forklift, golf cart, railway vehicles Telecom, UPS, utility switching, emergency power	5,000 – 50,000	(AS) IEC 62619 (batteries) UL 2580[42] (electric vehicles) UL 2271[43] (light electric vehicles)	Various, application dependant
Cells for HEV and BEV	10 – 1000	IEC 62660[44] series (batteries for electric vehicles)	None known
Motive (road vehicles)	5,000 – 50,000	UN100/R03[45] and ADR109/00 (DRAFT)[46] (electric vehicle power trains)	Australian Design Rules, via the Commonwealth Motor Vehicle Standards Act 1989
Electric vehicles energy storage systems	5,000 – 50,000	ISO 12405[47] series (traction battery packs and systems) ISO 6469[48] series (electrically propelled road vehicles) ISO 19453[49] series (road vehicles) SAE J2464[50] (electric and hybrid vehicles)	None known
Transport of dangerous goods, Li batteries	All	UN Part II, S38.3[51] (batteries) IEC 62281[52] (batteries)	Dangerous Good Act 1985, National Transport Commission, Australian Transport Code for all non-prototype products

31 IEC 60084-4 *Primary batteries - Part 4: Safety of lithium batteries*

32 IEC 62133-2 *Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications - Part 2: Lithium systems, is cell level*

33 UL1642 *Lithium batteries*

34 JIS C 8714 *Safety tests for portable Lithium Ion secondary cells and batteries for use in portable electronic applications*

35 UL 2054 *Household and Commercial Batteries*

36 ANSI C18.5 *Portable Lithium Rechargeable Cells and Batteries – General and Specifications*

37 IEC 62619 *Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries, for use in industrial applications, is system level and includes tests of BMS and includes propagation testing*

5.1.4 Other applications/environments

Because of the wide applications in which lithium-ion batteries are used and related capacity range, various standards have been written to provide a level of safety for their use. Table 6 details some of the most relevant product and safety standards for cells and batteries. Requirements for associated transformers, power suppliers and chargers, or battery management systems may be provided within these or other related standards.

Lithium-ion batteries are regulated as dangerous goods for the purposes of transport by road and rail. The Australian Dangerous Goods Code (ADGC), issued by the National Transport Commission, requires that all non-prototype lithium-ion batteries are tested in accordance with the UN Manual of Tests and Criteria (ST/SG/AC.10/11) Part II Section 38.3 *Lithium metal and Lithium-ion batteries* (commonly referred to as UN 38.3). Compliance to UN38.3 is the basis of dangerous goods classifications of loose lithium-ion cells (UN3480) of lithium-ion cells packed with equipment (UN3481).

Due to the mandatory nature of these transport regulations, the shipping of non-prototype amounts of cells by a manufacturer is prohibited without demonstrated compliance. In this way, UN 38.3 is, in the current regulatory environment, acting as a pseudo-mandatory standard for both locally and internationally produced lithium-ion cells.

In particular, it should be noted that an Australian manufacturer that wishes to demonstrate compliance of their (prototype) cells to UN 38.3 are currently required to either ship products overseas for testing, which is difficult and expensive due to the nature of the product being shipped and obvious lack of compliance documentation available. When a design is varied such that the prototype previously testing is no longer representative of normal manufacture, further testing is required under the same limitations.

Additionally, manufacturers of multi-cell batteries, or packs of batteries, are subject to the same requirements. Within UN 38.3, the following definition for 'battery' is provided:

'Battery means two or more cells or batteries which are electrically connected together and fitted with devices necessary for use, for example, case, terminals, marking or protective devices. Units which have two or more cells that are commonly referred to as 'battery packs', 'modules' or 'battery assemblies' having the primary function of providing a source of power to another piece of equipment are for the purposes of the Model Regulations and this Manual treated as batteries.'

The ADGC requirement therefore can be argued to extend to assemblies of cells and/or batteries (into packs, modules etc) even if the constituent cells and/or batteries have previously been tested to UN 38.3. In other words, the test requirements of UN 38.3 should, according to the mandatory ADGC, be applied to all non-prototype battery assemblies. In the absence of Australian testing options, it is unlikely that this mandatory compliance policy is currently being implemented.

5.2 Abuse test methods

Many standards include various test methods intended to expose products to 'off-normal' conditions to evaluate their response. Table 6 summarises the tests that are included in a range of published standards, noting that specific test requirements may differ.

Typically, each test method (crush, shock, short-circuit, etc.) has associated criteria for what constitutes a pass, such as no fire developed, or battery disassembly (i.e., rupture or explosion). In some cases, an internal fault is deliberately triggered, such as with propagation testing, in which an assembled pack of batteries is being tested for its ability to resist spread of damage.

38 IEC 61427 *Secondary cells and batteries for renewable energy storage - General requirements and methods of test - Part 1: Photovoltaic off-grid application*
39 AS/NZS 5139 *Electrical installations - Safety of battery systems for use with power conversion equipment*
40 UL 9540 *Energy Storage Systems and Equipment*
41 UL 9540A *Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems*
42 UL 2580 *Batteries for Use In Electric Vehicles*
43 UL 2271 *Standard for Batteries for Use In Light Electric Vehicle (LEV) Applications*
44 IEC 62660 *Secondary lithium-ion cells for the propulsion of electric road vehicles*
45 https://unece.org/sites/default/files/2022-07/R100r3e.pdf
46 ADR109/00 *Vehicle Standard (Australian Design Rule 109/00 – Electric Power Train Safety Requirements*)
47 ISO 12405 *Electrically propelled road vehicles — Test specification for lithium-ion traction battery packs and systems*
48 ISO 6469 *Electrically propelled road vehicles — Safety specifications*
49 ISO 19453 *Road vehicles — Environmental conditions and testing for electrical and electronic equipment for drive system of electric propulsion vehicles*
50 SAE J2464 *Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing*
51 UN Manual of Tests and Criteria (ST/SG/AC.10/11) Part II Section 38.3
52 IEC 62281 *Safety of primary and secondary lithium cells and batteries during transport*

Table 6 Existing standards and included test methods/type for abuse testing of batteries

TEST TYPE	UN 38.3	IEC 62133-2	IEC 62281	IEC 62660-2	IEC 62619	UL 1642	UL 2054	UL 2271	UL 2580	ANSI C18.5	SAE J2464	JIS C8714
External Short Circuit	✔	✔	✔	✔	✔	✔	✔	✔	✔		✔	✔
Abnormal/ Overcharge	✔	✔	✔	✔	✔	✔	✔	✔	✔		✔	✔
Forced discharge	✔	✔	✔	✔	✔	✔	✔	✔	✔		✔	
Crush		✔		✔		✔	✔	✔	✔		✔	✔
Impact	✔		✔		✔	✔	✔		✔	✔		
Shock	✔	✔	✔	✔		✔	✔	✔	✔	✔	✔	
Vibration	✔	✔	✔	✔		✔	✔	✔	✔			
Heating	✔	✔		✔	✔	✔	✔	✔	✔		✔	✔
Temperature cycling	✔		✔	✔		✔	✔	✔	✔	✔	✔	
Altitude	✔	✔	✔			✔		✔				
Projectile						✔	✔	✔	✔			
Drop		✔	✔		✔			✔	✔		✔	✔
Penetration								✔	✔		✔	
Internal short circuit		✔			✔						✔	✔
Fire exposure						✔	✔		✔			

5.3 Suitability of standardisation environment

The suitability of the current regime of standards and regulations should be judged on the risk presented to the users of products that include lithium batteries. Determining this risk requires an understanding of both the consequence of an unwanted outcome and its probability. A comparison between the apparent risk and community expectations may then be made, and standards and regulations adjusted if it is deemed necessary.

Even given known fault paths, it is difficult to judge the potential risk presented to consumer products containing lithium-ion batteries. This is because, while battery-related fires are often high profile and garner media attention, the actual rate of occurrence of battery-related fires in the community is not readily available. From the limited data available, it may be estimated that approximately 1% of all fires responded to by emergency services are currently battery-related, with the rate currently approximately doubling every two years. The fraction of fatalities related to battery-related fires is estimated to be approximately the same (1%), but low overall numbers of fatalities make the comparison difficult.

A detailed review of the abuse testing standards for lithium-ion batteries in electric and hybrid electric vehicles was published in 2018 by members of the European Union.[53] A key recommendation of that review was that tests for internal short circuits (and by implication, standards that include them) be more widely adopted in the legislative landscape, and that further research conducted to develop suitable and practical test methods. The same recommendation may be reasonably applied to smaller consumer items, given that the battery type and format used by EVs and other smaller consumer items are commonly the same (i.e., 18650 cells). To address this, regulation (through creation of mandatory standards as discussed elsewhere in this report) referencing forced internal short-circuit tests should be established.

Various factors leading to the initial circumstances required for fire conditions are described below.

53 https://doi.org/10.1016/j.rser.2017.05.195

5.3.1 Manufacturing quality control

For cells, manufacturers have numerous layers of quality control/quality assurance through receipt of individual components, the coating of electrodes, cell winding or stacking, and cell formation, ageing and grading, to ensure that all cells are delivered with the required capacity and voltage. However, in the absence of environmental effects (collision, external fire, etc.) failures within Li-ion batteries may arise due to internal faults from manufacturing defects such as where foreign object debris (FOD) may have been introduced to the cells. Such faults may lead to short-circuit and potentially thermal runaway and fire.

For high-quality manufacturing processes, it is expected that such faults would occur at a rate of less than 1 in 10 million units (batteries). It should be noted that an 'excellent' rated BMS (see Section 2.2) would be able to pick up the presence of such debris. The standards listed above are not intended to address this type of risk.

Product certification schemes, such as those accredited by the Joint Accreditation System of Australian New Zealand (JASANZ) to ISO 17065, may include aspects of factory production control to verify a level of quality control. It should be noted that a high sampling (testing) rate is likely to be required to verify mass production quality through analysis techniques such as x-ray computed tomography (CT) scans. In the absence of known defect levels during manufacture, which would vary between manufacturers, it is not viable to estimate the risk to consumers arising from this hazard category.

5.3.2 Normal use and misuse

Some consumer products containing lithium-ion batteries entering the Australian market are subject to existing (state-based) electrical safety regulations co-ordinated by the Electrical Regulatory Authorities Council.[54] Many of the essential safety requirements for electrical equipment as given by AS/NZS 3820, which applies to all products that 'store, insulate, use, convey or control' electricity such as batteries, toys, appliances and tools, may be met through compliance to the nominated lithium-ion battery related standards listed above, where relevant to the product type.

As discussed above, various abuse testing standards have been developed to verify the suitability of design and ability to withstand reasonable normal operating and misuse conditions of lithium-ion batteries and/or products that include them.

Largely, the electrical safety regulatory environment for consumer products may be based on self-declaration of conformity to relevant standards. In the absence of any form of mandatory product compliance regime as applies to some product types,[55] it is generally impossible to identify which batteries, or products containing them, claim compliance to any particular standard. Therefore, in the event of a battery fault, generated through internal (manufacturing fault) or external (e.g., impact) stimulus, forensic examinations are hampered with respect to determining the significance of conformity to a standard. The result is that it is difficult to differentiate between batteries (and/or products containing batteries) that fail but never met (nor claimed to meet) a particular standard and those that fail even though they were shown to meet a particular standard, making judgements about suitability of the standards themselves largely speculative.

An aspect that the existing standards do not cover well are the specific Australian climatic conditions that may be reasonably expected to exist around stationary energy storage systems that include lithium-ion batteries. Northern Australia commonly experiences high temperature and high humidity conditions, often in conjunction with highly corrosive environments; Central/Western Australia experiences very high temperatures for a large portion of the year. While many standards have some test conditions related to high temperatures (thermal or heating tests), none appear to include long-duration thermal tests, or provide options for increasing the severity of short-term tests to accommodate extreme end-use environments. Similarity, no standards include any resistance to corrosion tests that may be relevant for large parts of urbanised Australia.

54 https://www.erac.gov.au

55 See https://www.productsafety.gov.au/product-safety-laws/safety-standards-bans/mandatory-standards

5.3.3 Unintended use

As discussed above, the current regulatory environment places the burden of selection and application of relevant standards in many product categories on the responsible agency putting the product on the market in Australia. Whilst standards such as AS IEC 62368.1 specify a range of standards that must be applied to batteries,[56] a large list of standards with no guidance is provided. Some of the referenced standards apply to batteries alone, while other referenced standards, such as AS IEC 62619 directly address equipment that includes, internally or externally, a BMS. An excerpt of AS IEC 62619 is shown in Figure 13, demonstrating the different battery system architectures are addressed.

In the absence of system test (i.e., battery and BMS), faults arising from incompatible or otherwise unsuitable BMS as described in Section 2.2 may not be detected within the applied compliance regime.

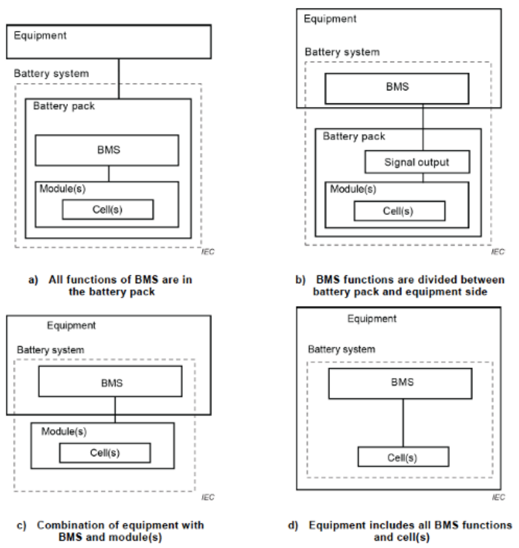


Figure 13 Excerpt from AS IEC 62619:2023 Figure 6 describing the various combinations of battery and BMS

5.4 Recommendations

Based on the information above, the following recommendations are made:

- Demonstrable compliance of lithium-ion batteries to either IEC 62133 (portable applications) and/or AS IEC 62619 (industrial applications). This is to be promoted through a combination of additional guidance in standards (such as in AS 62368.1) and regulatory enforcement options such as the establishment of mandatory certification (by JASANZ accredited bodies, etc.) of products containing lithium-ion batteries to relevant standards for their product type and/or application. This approach could facilitate improved quality control of the manufactured products, reducing the likelihood of random faults resulting in hazards during a product's lifetime. It will also provide an elevated level of assurance that batteries are able to withstand normal and foreseeable abnormal conditions during their duration.
- With increased levels of (demonstrated) compliance established, the suitability of the standards/criteria applied will be more apparent through analysis of statistics of fault events (e.g., fires). In other words, if the number of such unwanted events does not decrease with increased levels of compliance, the existing standards may be further assumed to be inadequate and in need of revision.
- Enforcement of existing requirements of the ADGC to ensure that cells and batteries imported into Australia, and potentially integrated into new equipment, meet the requirements of UN 38.3. The overlap between requirements of IEC 62133-2, AS IEC 62619 and UN 38.3 will simplify the required compliance (i.e., testing) pathway for manufacturers, importers, and potentially regulators.
- Additional testing facilities to be funded and established within Australia to provide sufficient capability to conduct tests on imported products to the standards nominated above, and to assist manufacturers in demonstrating compliance of Australian-produced cells and batteries.
- The availability of local testing options will reduce the barrier to market to manufacturers who currently need to send products overseas for testing, which is currently difficult and expensive due to limitations and hazards related to transport.

56 See Section M.2 of AS IEC 62368.1:2022

- Ensured access to UN 38.3 test capability within Australia will provide a method to comply with existing transport regulations, which may be currently being avoided through *ongoing* production and shipping of *prototype* products.
- Capability for the required tests for assessment of fire hazard such as UL9540A, from cell to unit level, is widely developed to support Australian manufacturing R&D, and safe expansion of the uptake of residential and commercial BESS. Module-level[57] testing requires substantial infrastructure due to the potential safety hazards involved in large-scale testing.
- Reliable statistical information is gathered from emergency services to provide an accurate estimate of the risk to the community arising from battery-related incidents (i.e., fires). The information should, if possible, include the number of events, types of products commonly involved and therefore battery sizes/capacities found to present the highest risk. While likely very difficult, the compliance of involved products should be determined to assist in the review of the suitability of existing standards.
- The collection of information would be ideally harmonised across all services operating in different states and territories to provide the largest data set possible.
- Where a BMS is provided as part of a product, the system should be tested accordingly, as described by AS IEC 62619 or other appropriate 'system' standard.
- Overarching safety standards, such as AS/NZS 62368.1, should include more guidance for the selection of test methodologies for lithium-ion batteries integrated within electrical products. Requirements for mandatory (compliance) marking of batteries may assist in the forensic determination of fault events as described in recommendation 1.
- The requirements of the ADGC are limited to testing (to UN 38.3) of individual cells or batteries prior to transport. Consideration to mandating the testing of assembled packs, if that is the form in which they are transported, should be given.

57 Modules will typically exceed 10 kWhr

6 Summary and recommendations

Lithium-ion batteries are now a ubiquitous part of our lives, powering our portable electronics, transportation solutions (e-scooters, e-bikes and vehicles) and, more recently, energy storage systems. A lithium-ion battery consists of several components, including cell(s), battery management system (BMS), wiring, external connection and, depending on the size of the device, potentially an active or passive cooling system. Each of these components plays a role in the safe operation of the device and, in the case of the BMS, is used to add multiple layers of safety to control a range of different failure mechanisms that can pose significant hazards to users. In this report, all these factors have been considered, including the role of charging systems, EOL considerations including second life and recycling and the standards and regulatory framework in Australia and how hazards to the public can be minimised from lithium-ion battery failure.

There are a range of commonly used lithium-ion battery chemistries identified in this report, and it should be emphasised that they all have a significant number of hazards if they are subject to abuse or used in 'abnormal' ways. Component failure can occur due to a range of factors, not necessarily due to users, and this can also lead to unintended consequences that could cause significant hazards to users. In the worst-case scenario, a battery can enter thermal runaway condition, which will include potential gassing, venting, smoke, fire, and explosion which is hazardous to people and property. Some battery chemistries are more prone to the later catastrophic failure mechanisms, specifically the high energy nickel and cobalt-based battery chemistries. Batteries based on LFP are considered safer, but they too can catch fire in off normal conditions. In many instances, users may not be aware of the specific lithium-ion battery chemistry that they are using and should endeavour to treat all these devices with care.

The BMS plays an important role in managing the cell(s) within a battery as well as managing and preventing a range of different failure mechanisms. There are four levels of BMS that encompass an ever-increasing range of capabilities in managing a battery, and it is recommended that standards agencies and regulators consider adopting a rating scheme to help inform users about the capabilities of a battery management system (BMS) in products and allow them to make informed choices. The future for BMS technologies is likely to include the move from wired to wireless systems that can maintain functionality, performance, and communication when failure occurs.

Chargers are provided with all battery products and play an important role in providing energy for charging a battery. The charger provides the appropriate current and voltage (energy) to the battery to charge it in a controlled manner. In many instances, a charger will communicate directly to the BMS to provide feedback on amount of energy to provide to the battery depending on its SoC. Where a charger fails, this can lead to several different failure mechanisms, but in the worst case, overcharging the battery, which can potentially lead to thermal runaway and fire as described earlier. All batteries should be charged with manufacturer specified chargers and that generic chargers are avoided. Users should also ensure that the charging cables and connectors are in good condition and always use manufacturer specified products.

Several hazards related to battery failure and the environments that batteries should be used in have been identified in this report. In particular, the hazards and risks associated with the inhalation of lithium-ion battery off-gasses from venting and smoke events as well as fire and explosion have been highlighted. Depending upon the size of the battery, the fire will be relatively small (portable electronics) or large (electric vehicle). If a battery enters any of the above conditions, users should move away immediately and call Triple Zero (000). If a person(s) inhales or comes in contact with these gases, solids or liquids, they should seek urgent emergency treatment in hospital. Users should always store batteries in an appropriate place when they are not in use and not in the fully charged state, as this is considered one of the most unsafe ways to store a battery. Charging of batteries should not be performed in confined spaces because of the potential hazard presented in the event of failure.

EOL of batteries, including second life and recycling of lithium-ion batteries, poses a significant hazard to users, the environment, and the public. For effective second life, whether it be the sale of second hand EVs or the repurposing of EV batteries, there needs to be standards and regulations around the information that is made available from a BMS that will provide information about the SoH of the battery. This will allow purchasers to make informed choices about batteries and their suitability. In the case of smaller battery systems, such as e-bikes, e-scooters, hoverboards, it is recommended that these are not available for second hand sale and where the batteries can be disconnected, they should be replaced, and the old battery sent for recycling. The collection and disposal of batteries, especially the standards and regulations, need to be harmonised.

The current collection, storage and transportation practices are not fit for purpose, potentially exposing people to hazards, and these need to be urgently addressed.

A range of Australian and International standards were identified as being relevant to lithium-ion batteries and products, which may include them as integral components. While some of these standards are currently referenced in current legislation or legislated schemes, there is a lack of verification and application of existing compliance. An increase in the level of compliance to existing standards may be enhanced through the increase in local (Australian) test capability such that importers, manufacturers, and products integrators are able to readily conduct conformity testing, in addition to new and enforceable product certification schemes.

Guidance within existing standards, and educational material made available to participants in the supply chain of Lithium-ion batteries, is lacking and clear direction to parties operating within the supply chain is required.

Appendix

A.1 Background on lithium-ion cell chemistry

The lithium-ion battery, as known today, was invented by Dr. Akira Yoshino in 1985 and then first commercialised by Sony and Asahi Kasei team in 1991. This work built on the seminal activities of Prof. Stanley Whittingham who used Titanium Disulfide (TiS_2) as a cathode for these batteries in 1974 and then, later, Prof. John B. Goodenough and his co-workers who identified Lithium Cobalt Oxide (LCO) as a stable and improved alternative to TiS_2 in 1980. However, the latter two inventions relied on the use of lithium metal as the anode for the cell, which was unstable and prone to fail and catch fire, leading to the need to find a more stable anode material. Yoshino's discovery of the use of a carbon host was the breakthrough that led to today's modern lithium-ion battery. In 2019, Yoshino, Whittingham and Goodenough were jointly awarded the 2019 Nobel Prize in Chemistry 'for the development of lithium-ion batteries'[58].

As shown in Figure 14, a lithium-ion battery is comprised of two 'active' materials - the cathode and anode that 'store' lithium ions typically by an intercalation method, a separator, electrolyte which shuttles the lithium ions between the electrodes and current collectors the take the electrons to/from the external circuit. A lithium-ion battery is a secondary or rechargeable battery in that lithium ions can be shuttled from the positive electrode (cathode) to the negative electrode (anode), described as 'charging' and from the anode to the cathode (discharging). When discharge occurs (left of Figure 14) a circuit is completed, external to the cell via the cell contacts, and a load is applied which causes the ions to move from the anode to the cathode. Depending on the size of the load connected, the ions will move faster (large load) or slower (small load), i.e., the discharge rate, and the resulting energy is used. In the case of charging (right of Figure 14) an electrical source, which provides a current to the cell, moves lithium ions from the cathode to the anode by a change in the potential difference between the two electrodes.

When a lithium-ion battery is charged, the electrical energy is being converted to chemical potential energy which is an endothermic reaction, i.e., it absorbs heat. In the event of discharge, the conversion of the chemical potential energy to usable electrical energy is an exothermic reaction, i.e., it generates heat.

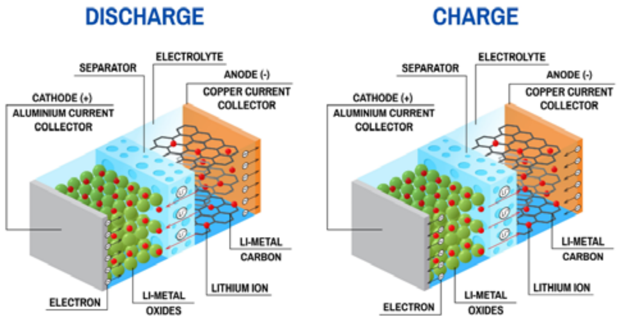


Figure 14 How a lithium-ion battery cell works in discharge (left) and charging (right) (Shutterstock)

In theory, if the process of moving ions from within one electrode to the other via the electrolyte was 100% efficient, i.e., there are no losses in the system, then a battery could theoretically last forever. However, due to the imperfect (electro)chemical reactions that occur both within the electrodes and at the interface of the electrode and the electrolyte, together with the impact of temperature, i.e., ambient conditions and Joule Heating, this is not the case. Consequently, during one charge-discharge cycle, if only 99% of the lithium ions are reversibly moved, then a battery would only last 100 cycles to lose all its capacity. If the system is 99.9% efficient, then the device would last 1000 cycles, 99.99% then 10,000 cycles and so-forth. However, as battery manufacturers define end of life (EOL) as 80% of initial capacity, then a 99% efficient battery would only last 20 cycles, a 99.9% battery 200 cycles and 99.99% battery 2000 cycles. The definition of EOL of a battery being 80% of the initial capacity is arbitrary and still allows for substantial usable capacity of the battery. Consequently, this has led to the development of 'second life' applications that are discussed in Section 4.1.

58 The Nobel Prize in Chemistry 2019 - NobelPrize.org

A.2 Battery electrodes, voltage and energy density

Most electrodes used in Li-ion batteries utilise a process of intercalation to store ions, whereby a mobile ion or molecule can be reversibly incorporated into the vacant sites of a crystal lattice. As an ion is incorporated into a lattice, an electron is removed to ensure charge neutrality. The exception to this is Li which is plated and stripped as a metal, and Si which is a conversion electrode. These will be discussed shortly. The capacity in Ah/g of an electrode is inversely proportional to the molecular weight of the material; consequently, Li metal is the most important electrode as it has the highest specific capacity of all electrode materials due to its incredibly light weight, as indicated in Table 7.

Table 7 Rechargeable lithium-ion battery electrode materials

ELECTRODE MATERIAL	ACRONYM	ANODE / CATHODE	SPECIFIC CAPACITY / MAH.G	VOLTAGE / V VS LI/LI+	TYPICAL USE
$LiCoO_2$	LCO	Cathode	> 140	3.9	Consumer devices
$LiFePO_4$	LFP	Cathode	~160	3.45	Consumer, Automotive, Energy Storage Systems
$LiNi_{1-x-y}Mn_xCo_yO_2$	NMC	Cathode	~200	3.8	Automotive, Energy Storage Systems
$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	NCA	Cathode	~200	3.8	Automotive, Energy Storage Systems
Graphite	G	Anode	360	0.05 to 0.1	All
Si	Si	Anode	3900	0.5	Automotive, Consumer,
Lithium	Li	Anode	3865	*0*	Primary batteries, next generation cell chemistry
$Li_4Ti_5O_{12}$	LTO	Anode	175	1.55	High Power applications

The total energy (E) stored in or discharged from a battery is the integral of its voltage (V) with respect to its capacity (C). Energy is expressed in Watt Hours (Wh) and can then be expressed in either gravimetrically (Wh/kg) or volumetrically (Wh/L), depending on which quantity is important to the application.

Table 8 describes cathode and anode combinations for commonly manufactured lithium-ion cells, the cell voltage and energy density and the applications that they are used in.

Table 8 Common electrode combinations for lithium-ion rechargeable batteries

CATHODE	ANODE	VOLTAGE / V	ENERGY DENSITY / WH/KG (WH/L)	APPLICATION
LFP	Graphite	3.2 – 3.3	90 –160 (333)	Consumer, Energy Storage Systems, Automotive
NMC	Graphite / Si	3.6 – 3.7	150 –220 (580)	Energy Storage Systems, Automotive
NCA	Graphite / Si	3.6	200–260 (600)	Energy Storage Systems, Automotive
LCO	Graphite	3.6	150 –200 (560)	Consumer

As Australia's national science agency, CSIRO is solving the greatest challenges through innovative science and technology.

CSIRO. Unlocking a better future for everyone.

Contact us
1300 363 400
+61 3 9545 2176
csiro.au/contact
csiro.au

For further information
Manufacturing
Dr Adam Best
+61 3 9545 8660
adam.best@csiro.au
csiro.au/manufacturing

B&M | 23-00339