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LITHIUM BATTERIES — WHAT'S THE PROBLEM?

BRANZ

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There is limited research on the number and impact of fires caused by lithium batteries in New Zealand. Fire and Emergency NZ (FENZ) incident statistics do not accurately capture battery specific information, making it difficult to fully appreciate the extent of the problem.

This research aimed to understand how lithium battery technologies contribute to fire risk and what can be done to mitigate.

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Lithium Batteries – What's the Problem?

George Hare

1222 Moonshine Rd, RD1, Porirua 5381
Private Bag 50 908, Porirua 5240
New Zealand
branz.nz

Preface

The 2019 Nobel Prize for Chemistry was awarded to John Goodenough, M. Stanley Whittingham and Akira Yoshino "for the development of lithium-ion batteries". The Royal Swedish Academy of Sciences went on to say, "Through their work, they have created the right conditions for a wireless and fossil fuel-free society, and so brought the greatest benefit to humankind."

Their low weight and high energy density have seen lithium-ion (LI) batteries being adopted in markets and devices that were previously not economic in terms of cost, weight or size. However, they have been shown to be susceptible to thermal run-away causing fires and explosions, resulting in significant injuries and loss of property around the world.

Fire & Emergency New Zealand (FENZ) has identified a growing trend over recent years, responding to an increasing number of incidents involving LI batteries.

This literature review was commissioned by FENZ to identify potential fire hazards associated with the proliferation of LI batteries in New Zealand society.

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Executive summary

A literature review was undertaken to identify the potential fire hazards associated with LI batteries and to inform FENZ of potential actions that could be taken to address the fire threat posed by these batteries. The study looked at incidents in New Zealand, as well as overseas and proposes the following recommendations for consideration by the sector:

1. All LI cells should be accurately labelled, to include the parameters required for safe operation. As a minimum, the cell voltage, maximum charging rate and maximum discharge rate.
2. A 'public education' programme should be developed covering:
    a. Safe use, disposal and recycling of old LI batteries,
    b. Correct charging of LI batteries,
    c. The risks of importing and using counterfeit LI batteries,
    d. Contacting Trading Standards or the Commerce Commission when faced with counterfeit batteries, or false claims around cell capacity.
    e. the potential risks associated with EV's being charged and parked in residential garages.
3. The installation of LI battery ESS or EV charging stations should require a building consent to ensure the installation meets the existing requirements of NZBC clause G9.
4. The insurance industry should be advised of the following potential risks:
    a. EV's being charged and parked in residential garages,
    b. The potential risk of losses as a result of 'juicing' operations.

This literature review has also identified the following areas where further research is needed:

5. Quantification of the joule effect when measuring HRR from LI cells during combustion.
6. An assessment of the risks to fire fighters, fire investigators and anyone else involved in the clean-up following an LI battery fire, including thermal, chemical and re-ignition risk. This risk may extend to insurance assessors, tradesmen and occupants.
7. The safety of LI based power banks when used to 'jump-start' vehicles.
8. Guidance on how to prevent spread of fire in the event of an ESS or EV thermal run-away failure scenario, or EV charger fault.

1. Introduction

Lithium-ion (LI) batteries are becoming ubiquitous in modern society, contained in everything from large-scale solar energy storage systems (ESS) or hybrid and electric vehicles (HEV), to smaller scale devices like laptops. Most portable electronic devices use single LI cells, for example cell phones, smart-watches and e-cigarettes. They are also now used extensively for higher-powered portable applications like power tools, remote-controlled vehicles, lawn mowers, bikes and scooters. Some of these applications include childrens' toys.

The push for ever higher energy densities for longer run-time or smaller size and higher discharge capabilities has led to the use of more compact designs and more unstable chemistries, resulting in increased numbers of thermal-runaway events, leading to fires, explosions and injuries around the world.

This study report undertook a literature review to look at the fire risks associated with LI batteries. For this purpose, data was drawn from a range of sources to assess the risk in New Zealand.

2. Background

Lithium is a reactive alkali metal and is the lightest metal in the periodic table. Its low atomic mass gives lithium a high charge to weight ratio, making it ideal for use in batteries. Lithium produces approximately 3 volts per cell, compared to 2.1 volts for lead-acid and 1.5 volts for zinc-carbon.

A battery is made up of multiple cells. Cells can be connected either in series to increase the voltage at the terminals, or parallel, to increase the available current, or both. However, single cells are often still referred to as batteries.

Primary cells are disposable portable voltaic cells that cannot be recharged easily after use. Secondary cells are portable voltaic cells that can be easily recharged, making them re-usable.

Lithium is used in both primary (non-rechargeable) and secondary (rechargeable) cells.

2.1 Primary Lithium Cells

Primary lithium cells are considered hazardous for a number of reasons, they contain a lithium metal anode (which is highly reactive), the electrolyte can be made of flammable organic solvents and they can contain potentially explosive components such as perchlorates (Libona, 2011). Primary lithium cells are generally small and not used in bulk in a single application, for example, a single 'coin' cell is used in a wristwatch. Larger primary lithium cells, such as the CR123A shown in Figure 2, are used in high power applications, such as torches.

They do not pose a significant fire hazard individually, but when transported in large volumes, they are classed as dangerous goods (DG). Class 9 is for miscellaneous DG and includes a diverse range of substances, not covered in classes 1-8. Class 9 should not be considered any less hazardous than classes 1-8. Class 9 includes asbestos (in various forms), some ammonium nitrate fertilisers, many environmentally hazardous substances as well as lithium batteries (Ministry of Transport, 2008).

Figure 1. Lithium 'CR2032' Coin Cell

Figure 2. Lithium 'CR123A' Cell

Source: https://www.panasonic-batteries.com

However, the hazards posed by primary cells are well known to FENZ. Consequently, these cells are not the focus of this report and will not be considered any further.

2.2 Secondary Lithium-Ion Cells

Secondary rechargeable lithium-ion cells use lithium oxides as an electrode, with a lithium-based electrolyte to transport charge between the electrodes during charge and discharge cycles, hence the name lithium-ion cell. They can be customised into almost any size/capacity but are generally cylindrical, pouch or prismatic in form-factor as shown in Figure 3.

Figure 3. Lithium-Ion Battery Form-Factor

Source: John Teel, https://predictabledesigns.com/

This report will consider only secondary LI cells

3. Lithium Battery Chemistries

Currently, LI batteries typically use a carbon anode in the form of graphite and use a variety of different cathode materials containing lithium. Lithium is also used as a charge carrier in the form of ions in a hydrocarbon-based electrolyte, usually lithium hexafluorophosphate salt, in ethylene carbonate/diethyl carbonate solvent. The solvent is highly flammable, with a flashpoint of 30℃ (Sigma-Aldrich, 2019).

There are five common cathode materials used in LI batteries. Each chemistry has its own characteristics, shown below in Table 1:

Table 1. Cathode Material Properties

Cathode Material	Nominal Cell Voltage (V)	Specific Energy (Wh/kg)	Charge / Discharge Rate	Cycle Life	Thermal Runaway Temperature
$LiCoO_2$ (LCO)	3.6	150-200	Charge 0.7-1C Max Discharge 1C Max	500-1000	150℃
$LiMn_2O_4$ (LMO)	3.7	100-150	Charge 0.7-1C Typ, 3C Max Discharge 1C Typ, 10C Max, 30C Pulse	300-700	250℃
$LiNiMnCoO_2$ (NMC)	3.6-3.7	150-220	Charge 0.7-1C Max Discharge 1C Typ, 2C Max	1000-2000	210℃
$LiFePO_4$ (LFP)	3.2-3.3	90-120	Charge 1C Typ Discharge 1C Typ, 25C Max, 40C Pulse	1000-2000	270℃
$LiNiCoAlO_2$ (LCA)	3.6	200-260	Charge 0.7C Typ Discharge 1C Typ	500	150℃

Source: BU-205, 2018

The capacity of a battery is measured in ampere-hours (Ah). This is a measure of the current it is able to supply, at the rated voltage, if it were fully discharged in one hour. For example, a cell with a capacity of 3200 mAh should deliver 3.2 amps for one hour. If the current is halved, then the cell should deliver 1.6 amps for 2 hours and conversely, if the current is doubled, then the time is halved, so a 3200 mAh cell should supply 6.4 amps for only 30 minutes.

The charge/discharge rate (C) of a cell is given in terms of multiples of its capacity. If, in the above example, a cell has a 1C charge rate and a 10C discharge rate, then it could be discharged at up to 32 amps (10 x 3.2 amps) and last for 6 minutes ($1/10^{th}$ of an hour) but should not be charged at more than 3.2 amps (1 x 3.2 amps), requiring at least an hour to charge back up to full capacity.

3.1 Lithium Cobalt Oxide ($LiCoO_2$)

Lithium cobalt oxide (LCO) batteries have relatively high specific energy but a low specific power. Charging or discharging an LCO battery at more than 1C can result in overheating. LCO also has a low thermal runaway temperature and is particularly prone to thermal runaway when charging or discharging above 1C.

LCO batteries are losing ground to other chemistries as a result of the cost of cobalt and the better performance of other cathode materials. However, these batteries are still commonly used in cell phones, tablets and laptops (BU-205, 2018).

3.2 Lithium Manganese Oxide ($LiMn_2O_4$)

Lithium manganese oxide (LMO) batteries have lower specific energy than LCO but are far more thermally stable. The three-dimensional spinel structure of the cathode material gives LMO batteries a very low internal resistance, allowing them to be charged and discharged at much higher rates than LCO. LMO batteries can typically be discharged at 20-30A with a moderate heat build-up but rarely exceed 80℃, even at continuous high load. This lends them to use in power tools, where fast charging and high loads are expected.

LMO batteries have a low cycle life compared to other cathode materials, as a result they tend to be used in a blended configuration with NMC batteries (discussed below) in the powertrain for HEV's, providing short bursts of high power for acceleration (BU-205, 2018).

3.3 Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$)

Lithium nickel manganese cobalt oxide (NMC) has high specific energy, high specific power, good thermal stability and long life, making it one of the most successful cathode materials that can be configured for either high capacity or high power, in the same size package. As described above, NMC batteries are used in conjunction with LMO batteries in HEV powertrains, industrial applications and E-Bikes (BU-205, 2018). Tesla use NMC batteries in their Powerwall and Powerbank products due to the longer life cycle performance (Maxim, 2018).

3.4 Lithium Iron Phosphate ($LiFePO_4$)

Lithium iron phosphate (LFP) has a lower specific energy and lower cell voltage than other cathode materials, it has the benefit of being very stable, which gives excellent cycle life and high specific power with much lower risk of thermal runaway, even if abused. This makes it the safest of the LI cathode chemistries currently on the market.

LFP are generally used in stationary systems. They are being used to replace lead-acid starting batteries in vehicles. Four LFP cells in series provide 12.8 volts, compared with a standard lead-acid battery 13.8 volts. There is some question as to how LFP batteries will fair in the long term as regular vehicle charging systems are designed to charge the battery at 14.4 volts continuously in operation (BU-205, 2018).

3.5 Lithium Nickel Cobalt Aluminium Oxide ($LiNiCoAlO_2$)

Lithium nickel cobalt aluminium oxide (NCA) has a very high specific energy. The addition of aluminium reduces the amount of cobalt required, reducing the cost. Coupled together, these two factors mean that NCA has the lowest cost per kilowatt hour of any current lithium-ion battery. This is the cell of choice for Tesla in their Electric Vehicle (EV) powertrain. However, they do suffer from a relatively low thermal runaway temperature (BU-205, 2018).

3.6 Lithium Titanate (Li_2TiO_3)

Lithium titanate (LTO) is an alternative anode material, usually used in conjunction with LMO or NMC cathode material. LTO has the lowest specific energy of the lithium-ion chemistries, lower than that of Nickel Metal Hydride (NiMH), but due to its low cell voltage and stable chemistry, is the safest LI chemistries currently on the market (BU-205, 2018).

Table 2. Anode Material Properties

Anode Material	Nominal Cell Voltage (V)	Specific Energy (Wh/kg)	Charge / Discharge Rate	Cycle Life	Thermal Runaway Temperature
$LiTiO_3$ (LTO)	2.4	50-80	Charge 1C Typ, 5C Max	3000-7000	250°C
			Discharge 10C Max, 30C Pulse		

Source: BU-205, 2018

3.7 Identification of Battery Type

Many batteries may be readily identifiable as lithium-ion as a result of their form-factor, or they may be labelled as "lithium-ion". However, few of them identify the chemistry of the battery to allow someone to make an informed decision around the precautions for use i.e. charging voltage, rate of charge/discharge etc. A contributing factor to the use of incorrect chargers/settings may be the lack of labelling and information, but further work would be required to investigate this.

It is recommended that all LI cells should be accurately labelled, to include the parameters required for safe operation. As a minimum, the cell voltage and maximum charging rate should be specified, not just the maximum discharge rate.

4. What is Thermal Runaway?

Thermal runaway results from an increasing cell temperature due to either external heating or internal heat generation within the cell. If the temperature continues to rise, the electrolyte will boil, causing an increase in pressure within the cell, as shown in Figure 4. The breakdown of the electrolyte in the cell is irreversible, once a cell undergoes this type of abuse, the cell is damaged permanently and should not be re-used, even if the cause of the overheating is removed.

If the pressure reaches a critical point, the cell can rupture, releasing flammable gases and, in some cases, projectiles at near transonic speeds (Mier et al., 2017). These gases have the potential to mix with oxygen in the surrounding air and form an explosive mixture. If an ignition source is present, the mixture will readily combust, further heating surrounding cells, and causing a cascade reaction.

4.1 External Heating

External heating is primarily the result of a fire or other external heating influence, such as another cell undergoing thermal runaway.

4.2 Internal Heating

Thermal runaway caused by internal heating can be caused by several different mechanisms:

- Physical damage; for example, crushing or puncturing can breach the thin insulator between the anode and cathode, causing a short circuit and localised heating. This category would also include potential manufacturing flaws such as contamination, poor welds, weld splatter, or flaws in the electrodes such as tears in the electrode or separator.
- Deep discharge can cause dendritic growth (tiny finger-like growths) of lithium, which can breach the thin insulator between the anode and cathode. This could cause a short circuit and prematurely discharge the cell. However, this is unlikely to cause sufficient heating to drive the cell to thermal runaway, due to the low charge state. When the cell is subsequently connected to a charger, the continuous heating provided by the current from the charger at the short circuit can causing sufficient localised heating to drive the cell to thermal runaway.
- Excessive charge or discharge current. A cell has a fixed internal resistance. When current is passed through a resistance, the power is dissipated in the form of heat. If the heat produced as a result of charging/discharging the cell cannot be dissipated fast enough, the cell temperature will rise accordingly.

The end result of the heating is the same as that for external heating.

Internal heating is potentially more dangerous from a fire-fighting perspective as there may not be the correct conditions for ignition to occur. Even if the heat source is enough to ignite the gases, there may not be sufficient oxygen in the environment around the cell to support combustion. Fire-fighting operations have the potential to introduce oxygen into the environment, promoting combustion and in some circumstances, for example if contained, explosion to occur (APS, 2019).

Figure 4. Swollen Pouch Cell

4.3 Contributing Factors

The State of Charge (SoC) of a cell is a measure of the current capacity of the cell with reference to its maximum capacity. A cell at 100% SoC is fully charged, whereas a cell at 0% SoC is fully discharged. The SoC has a significant impact on the stability of the cell.

4.3.1 High Charge Level

A high SoC increases the likelihood of thermal runaway. Testing at Sandia Laboratories on a commercial LCO cell exhibited thermal runaway at 80 °C for a cell at 100% SoC and 130 °C at 0% SoC (Roth, 2000).

4.3.2 Low Charge Level

Deep discharge of cells promotes growth of lithium dendrites during charging, which can then puncture the very thin separator membrane, causing a short circuit. This becomes a problem as the current causes the area around the short circuit to heat up rapidly, initiating thermal runaway as described above.

4.4 Battery Management Systems

Battery Management Systems (BMS) are an electronic circuit used to monitor the condition of a cell or battery. Depending upon the complexity of the battery, the BMS can perform a number of different roles.

The primary safety role is to prevent the cells from over-charging beyond the maximum cell voltage (sometimes less, to improve the life of the cells) and to prevent the cells from discharging to a point where dendrite can begin to form. By maintaining the cell within the limits specified by the manufacturer, the life of the cell is optimised.

A BMS may also perform either active/passive balancing of the cells within a battery. Balancing cells is the process of sharing charge equally between them, when connected in series. A series connected battery is only as good as the weakest cell, so if a single cell becomes degraded by over-charging, then it reduces the overall performance of the battery.

A BMS may also monitor the temperature within the battery pack. If the temperature exceeds the specified safety level, it may either provide an alarm signal, or in some cases, cut off the power to/from the battery to allow the battery to cool to within normal limits. Sophisticated battery packs incorporate active cooling systems to maintain the battery temperature within an optimal range for performance (Mearian, 2016).

A BMS cannot normally stop a thermal runaway event once it has been initiated, the BMS is primarily designed to prevent the onset of thermal runaway.

Not all batteries are equipped with a BMS. For example, the battery packs used for model aircraft and many other hobby vehicles do not have a BMS, they are simply cells connected together, in a single package. In the example below, 3 cells are connected in series to produce an output of 11.1 volts, 3.2Ah. Note also the high discharge capacity of 64 A (20C x 3200mAh) but no indication, on the labelling, of what the battery charging current should be.

Figure 5. 3-Cell lithium battery

Source: Wikimedia, No copyright

Where a battery has no BMS, correct charger selection and operation are imperative, as over-charging of LI cells is a significant driver for thermal run-away.

This type of battery (shown in Figure 5) is commonly used in radio-controlled vehicles and other children's toys and is particularly susceptible to being over-charged. These batteries do not tend to be supplied with a charger specific to the battery, users may purchase multiple batteries and a single generic charger. This can result in different chemistry batteries being plugged in without the appropriate settings being altered in the charger.

Not all chargers support balancing of cells. In Figure 5 at the lower left side of the battery, a balancing lead can be seen. This is connected to the terminals of each cell, so for the 3-cell battery shown, there would be four leads as shown in Figure 6 below.

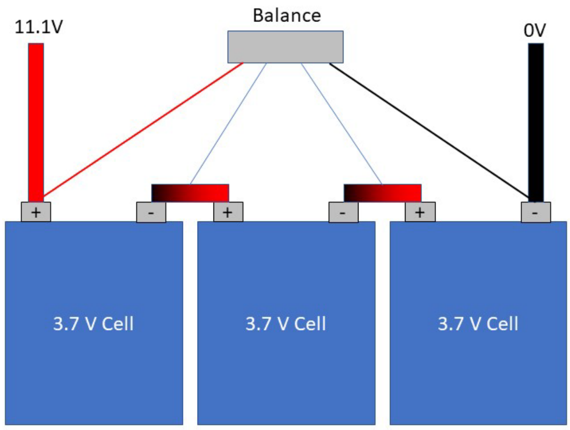

Figure 6. Lithium Battery Balancing Connections

By measuring the voltage at each cell terminal, the charge can be interrupted if the cells are not balanced and charging evenly. Some 'intelligent' chargers are able to use this feature to discharge cells that are over-charged, to balance all of the cells.

Some chargers do not have a time limit on charging. Good quality chargers will manage the charge by monitoring the current, voltage but, also have a 'watchdog timer' to stop the charging after a specific time period has elapsed, even if the cell voltage has not reached the required value.

4.5 Correct Charger Selection

Different battery types require different charging characteristics from the charger. Chargers suited to charging other battery types (lead-acid, NiCad, NiMH) are not suitable for charging LI batteries, the cell voltages are different and the charging regime (constant-current, constant-voltage) are not the same. From incidents reported to Energy Safety New Zealand (ESNZ) that relate to the wrong charger being used, it can be surmised that the general public has a lack of understanding around battery charging. Even though most products state on them that 'only the charger supplied' with the device should be used, there appears to be a misconception that 'a charger is a charger…. right?'

Even where the right type of charger is selected, the specification of the charger output or cable may not be compatible with the device being charged, for example many portable devices use a USB charger. However, the USB specification has evolved over time, some chargers many only be able to deliver 0.5 amps @ 5 volts to the device, whereas others may be able to deliver 3-5 amps @ 20 volts for devices capable of fast charging. The cable used to connect the USB charger may also have an effect on the rate of charging, for example a Huawei Mate 20 Pro, charged with the supplied charger and cable can charge at 32.45 watts but the same phone, with the same charger but an LG cable may only charge at 15.15 watts [Android Authority, 2019].

Chargers are available on the market that are able to be configured to different battery types. For example, the popular iMAX B6 charger, has settings for lead-acid, NiCad, NiMH and LI batteries. However the individual cell voltage cannot be adjusted, so where the charger might be fine for use with LCO, LMO, NMC or NCA batteries, where the cell voltage is around 3.6-3.7 volts, it would not be ideal for LFP or LTO cells, where the cell voltage is lower (3.2-3.3 or 2.4 volts respectively).

It is recommended that there should be a 'public education' programme around the safe use of lithium-ion batteries and the correct charging of them.

4.6 Hazards

4.6.1 Thermal Effects

When LI batteries reach thermal runaway, the results can be catastrophic. Not only are there flammable gases that can be released upon rupture of the cells, but the pressures attained can result in hot projectiles being ejected at high near transonic velocities (Mier et al., 2017). As the gases burn, they can in-turn heat up surrounding cells and cause them to go into thermal runaway. This is called a cascade reaction.

The intensity of the fire is normally dependent upon the size and SoC of the cell. A study of a commercially available 2.9 Ah pouch-type cells that, for a given cell size, the total chemical heat release is a constant regardless of SoC. However, the period over which the heat is released, and the peak heat release rate (HRR) is highly dependent upon the SoC. A cell at 100% SoC had a peak HRR of 21 kW over a period of approximately 20 seconds. At 50% SoC, the same type of cell had a peak HRR of 13 kW but burned for a longer period, approximately 50-100 seconds. At 0% SoC, the peak was only 2.6 kW but burned over a period of approximately 300 seconds (Ribière et al., 2011).

It should be noted that the HRR was measured using a Tewarson calorimeter (also known as the FM Global Fire Propagation Apparatus) which calculates HRR based on oxygen consumption and therefore only considers the chemical heat released.

Although the cells tested by Ribière et al. were driven to thermal runaway by external heating, the normal initiation process for thermal runaway is a short-circuit within the cell. The electrical energy being dissipated across the short-circuit releases heat (the joule effect). The Tewarson calorimeter does not take account of this additional heat release as the insulator in the cell begins to melt and cause further short-circuits with the cell. This additional heat release from the joule effect increases with the SoC and would account for the more energetic release of the total chemical heat release.

For example, the 2.9 Ah, 3.7 V cell tested by Ribière et al. contains ~11 Wh of electrical energy. If that 11 Wh was dissipated over 20 s (100% SoC) as the insulator melts in a fire, that would equate to an additional 2 kW being released. It is the author's opinion that the release of electrical energy happens over a much shorter timeframe than the chemical release and therefore contributes a much more significant proportion of the peak heat released than that measured by a Tewarson calorimeter.

Further work is required to account for the joule effect when measuring HRR from LI cells.

Given that many devices containing LI batteries (cell phones, vaping devices, etc.) may be carried in clothing or held, there is the possibility for direct harm to result from a thermal runaway event in the form of severe burns (Jolly, 2019).

If the initial fire is big enough, or in close enough proximity to other combustible materials, then the fire has the potential to grow and put many more lives at risk.

4.6.2 Toxic Products

Far more people die from smoke inhalation than from direct exposure to fire and many more are hospitalised for treatment related to the effects of smoke inhalation after a fire (Alarifi, Phylaktou and Andrews, 2016).

The solvents used in the electrolyte in LI cells are normally hydrocarbon based. ethylene carbonate ($C_3H_4O_3$) and diethyl carbonate ($C_5H_{10}O_3$) are commonly used solvents. In a fire, depending on the available oxygen, they will typically evolve into carbon monoxide (CO), carbon dioxide (CO_2) and water (H_2O). However, there are far more potent constituent parts in an LI cell. The lithium salt commonly used in the electrolyte is lithium hexafluorophosphate ($LiPF_6$), the binder commonly used for the electrodes is polyvinylidene fluoride or PVdF ($C_2H_2F_2$). Both of these compounds contain fluorine. As the electrolyte breaks down, phosphorous pentafluoride (PF_5) is released, this combines with water released during combustion of the solvents, to evolve phosphoryl fluoride (POF_3) and hydrogen fluoride (HF), both of which hydrolyse rapidly with water to form phosphoric acid and hydrofluoric acid respectively (Larsson, Andersson, Blomqvist & Mellander, 2017).

Phosphoric acid is considered a medium-strong acid according to the International Chemical Safety Card database (ICSC, 2019a), it can cause redness, blistering and burns to the skin and eyes. The WorkSafe NZ time weighted average (TWA) exposure limit for phosphoric acid is 1 mg/m^3 over an 8-hour workday (WorkSafe New Zealand, 2018) and is in-line with other international jurisdictions. For example Work Safe Australia use a TWA of 1 mg/m^3 over an 8-hour workday and a short-term exposure limit (STEL), for exposure over 15 minutes, of 3 mg/m^3 (HCIS, 2019a).

Hydrofluoric acid is considered a weak acid according to the International Chemical Safety Card database (ICSC, 2019b), it can cause redness, blistering, pain and burns to the skin and eyes, it is also readily absorbed into the skin. The Worksafe NZ TWA exposure limit for hydrofluoric acid is 2.6 mg/m^3 over an 8-hour workday (WorkSafe New Zealand, 2018) and is in-line with other international jurisdictions. For example, Work Safe Australia use also a TWA of 2.6 mg/m^3 over an 8-hour workday. Neither jurisdiction specify a STEL (HCIS, 2019b).

Both acids react with metals, releasing hydrogen gas, which is an explosion hazard, especially where ignition sources may be uncovered during overhaul in a fire scenario.

Analysis of the production of gases during combustion has also found a correlation between the SoC and the production of some toxic species (Sun et al., 2016 and Lecoccq et al., 2016). The total measured HF released from the 2.9 Ah pouch cell tested went from 408 ±30 mg at 100% SoC up to 757 ±24 mg at 0% SoC (Ribière et al., 2011).

They compared the quantities of gases released to the Irreversible Effects Threshold (IET) and the First Lethal Effects Threshold (FLET). The scenario used the same values from the ~11 Wh pouch cell (757 mg of HF) and assumed the gases would be spread evenly in a fictitious 50m^3 room and then calculated the size of battery required to reach the IET and FLET thresholds for 60 minutes exposure. Based on their calculations, they determined that 60 Wh would be required to achieve IET and 110 Wh to reach FLET (Ribière et al., 2011).

To better quantify these levels, in a room 4 m by 5 m by 2.5 m high (a large office) a single laptop battery (40-110 Wh) has the capability to release enough HF to reach the threshold for IET/FLET.

It is unclear at this point if the numbers scale linearly but, if they do, consider an EV in a single garage (6 m by 3 m by 2.1 m high) of ~$40m^3$. A space 20% smaller with a battery potentially up to 1000 times the capacity.

A Swedish study showed that, when heated to thermal runaway, LFP cell produced significantly lower volumes of gas (42L/kg), when compared to NMC/LMO cells (780L/kg). However, the volumes of HF were comparable, indicating that the concentration of HF coming off LFP cells to be higher than that of NMC/LMO (Sturk, Rosell, Blomqvist and Tidblad, 2019). It should be noted that these experiments were conducted in an inert atmosphere, which is not representative of a fire scenario, where oxygen would likely be present, changing the potential effluent products.

Using a modified Single Burning Item (SBI) test apparatus HF production was measured during combustion of a variety of cells (primarily LCO and LFP). Between 20 and 200mg/Wh of the nominal battery capacity were measured (Larsson, Andersson, Blomqvist and Mallander, 2017).

Further work is required to fully understand the risks to fire fighters, fire investigators and anyone else involved in the clean-up following an LI battery fire. This risk may extend to insurance assessors, tradesmen and occupants.

5. Counterfeit Products

Although the price of LI cells has steadily come down over the years, the main manufacturers (Samsung, Panasonic and LG Chem) are still able to charge premium prices for their cells. This has opened up a large market for imported cells that are either counterfeit or from less reputable manufacturers. There are two main threats around counterfeit products, those that claim to be made by another, more reputable manufacturer and those that make unrealistic claims around the cell performance (capacity and/or charge/discharge rate).

5.1 Manufacturer

Consumers are being fooled by batteries claiming to be from Original Equipment Manufacturers (OEM's) but are in-fact being replaced by sub-standard alternatives. For example, in 2017 Samsung Electronics New Zealand Limited investigated after a fire involving a Samsung Note 4. An analysis of the remains of the battery determined that although the battery was marked as a Samsung SDI battery, the Protection Circuit Module (PCM) on the end of the battery did not match Samsung SDI, Sanyo (Panasonic) or Hitachi. The retailer claims that the battery was bought directly from Samsung SDI (ESNZ, 2019).

5.2 Performance Claims

Some manufacturers are making questionable claims about cell capacity and discharge rate, as shown below in Figure 6. Current limitations on cell chemistry mean that it is not physically possible to fit the energy density claimed into an 18650-size cell but unfortunately, the general public take these claims at face value. With current technology, anything claiming more than 3500-3600 mAh in an 18650-size cell is likely to be unrealistic.

Figure 7. 9800 and 12000 mAh Cells on AliExpress

These manufacturers tend to have less quality control around manufacturing processes (Narayanan, 2014), resulting in more faulty cells making it to market as a result of imperfections like weld splatter, damaged insulators, etc., making them more susceptible to thermal runaway (Abraham, 2016).

Excessive claims around discharge capacity are also matched with excessive claims around the charging rate, this is potentially more dangerous as users would normally be alerted to a fire during use but might be asleep when the cells are being charged.

It is recommended that Trading Standards should be contacted and advised of the false claims around cell capacity. Guidance should also be given to consumers and retailers on the risks of importing and using counterfeit products.

6. Market Size in New Zealand

An attempt has been made to quantify the size of the LI battery market size in New Zealand. This has proved very difficult as there are so many devices on the market containing these batteries, with no single source of data.

Batteries can be split into two categories, large and small, based on the capacity of the battery pack. For example, a large battery pack might be constructed using hundreds or thousands of small cells. For the purposes of this study report, batteries of more than 1 kWh are considered large. Large batteries are mainly used in ESS's and HEV's.

6.1 Energy Storage Systems

ESS's can again be split into two different markets;

- Residential / Commercial
- Network

The residential / commercial market is being addressed by a growing number of retailers, big and small, marketing systems from large reputable manufacturers such as Tesla, Panasonic and LG Chem to smaller, less well known, manufacturers. For example, Tesla market their Powerwall product (13.5 kWh) directly to the public, through their website, but also through retailers. Harrisons Energy offer both the Tesla Powerwall product as well as the Panasonic 'All-in-one' Battery Storage System (6.4 kWh). Other retailers offer similar products, for example ZEN Energy Systems offer both the LG Chem RESU (3-9 kWh) battery system and the PylonTech US2000B Plus (2 kWh).

There are currently no consent requirements for the fitting of LI ESS (discussed further in Section 10). However, testing by Tesla Inc. on their Powerwall 2 (DNV GL, 2019) has shown that, in the event of a thermal runaway failure, when installed on a combustible cladding system (such as timber weatherboards used in New Zealand), fire can propagate quickly beyond the confines of the ESS, spreading up the wall surface and into the roof space above.

It is recommended that installation of an ESS should require a building consent to ensure that the installation does not prejudice the fire safety of the property.

Much bigger systems, such as the Tesla Powerpack (100 kWh) have been deployed within the electricity network, for managing demand, voltage and frequency regulation. In August 2018, Mercury Energy unveiled a 100 MWh battery system at their test facility in south Auckland, at a cost of almost $3M (Mercury, 2018).

A discussion document released by Transpower in 2017 has recommended that even without Photovoltaic (PV) panels to charge an ESS, there is benefit to the homeowner and the network for having an ESS to smooth out demand and reduce costs to the grid(Transpower, 2017).

Of concern is a growing trend in DIY 'powerwall' systems. These are home-made ESS's usually made up of reclaimed LI cells from laptop batteries, bare 18650 cells or second-hand cells removed from EV's. Most have limited or no BMS at all. The Facebook group 'DIY Poweralls' has over 29,000 members around the world. Kiwi's are known for their DIY, 'give it a go' attitude, so this potentially poses a far greater threat to fire safety than commercially supplied systems. There has been a fire incident recorded in New Zealand with a DIY system, discussed further in section 7.1.

At this stage it is unknown how many and what capacity ESS systems have been installed in New Zealand homes, businesses and networks.

6.1.1 Hybrid & Electric Vehicles

A study of the NZTA open data set up to April 2019 shows that, of the 5.3 million vehicles currently registered on NZ roads, approximately 52,500 are hybrid or full electric vehicles. NiMH currently accounts for 70% of the HEV market. This is primarily due to the earlier adoption of NiMH chemistry, with the first vehicles being registered in New Zealand in 2001, compared with 2008 for LI chemistries. However, since LI chemistries have become more popular as a result of higher energy density and lower weight, the take up rates have exceeded that of NiMH. For example it took 14 years for NiMH vehicle registrations to reach just under 11k, whereas LI vehicle registrations have exceeded 13k in 11 years as shown below in Figure 8.

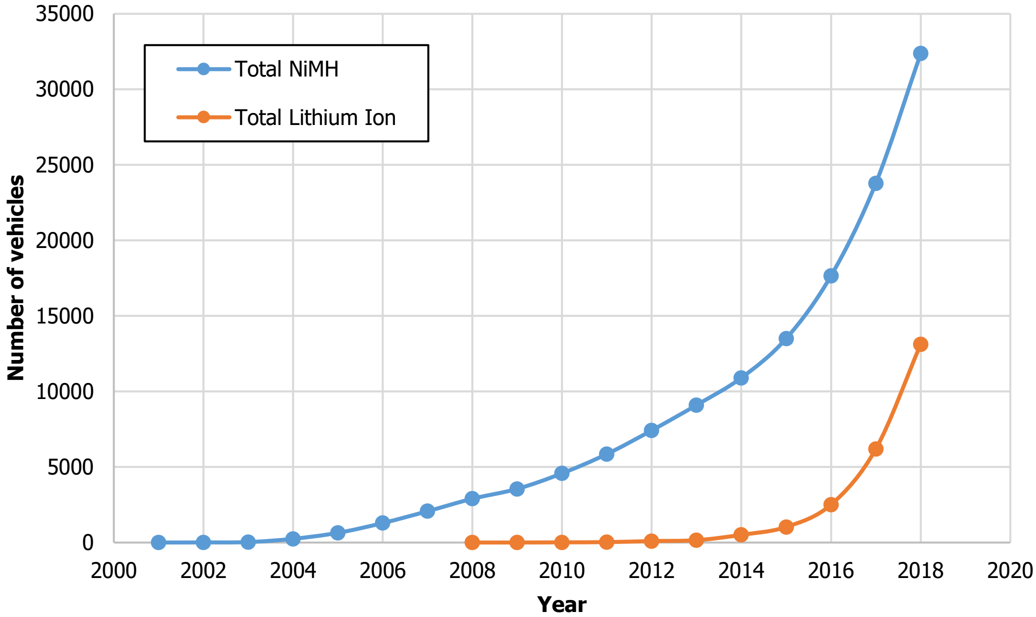

Figure 8. Hybrid & Electric Car Registrations in New Zealand

Hybrid battery packs tend to be smaller as they are supported by an internal combustion engine as required. Table 3 below gives an indication of the capacities of some full EV and HEV's registered in New Zealand.

Table 3. HEV Battery Capacities

Make	Model	Hybrid / Full EV	Battery Capacity
Nissan	LEAF	Full EV	24-30 kWh
Tesla	Model 3	Full EV	50-75 kWh
Tesla	Model X	Full EV	60-100 kWh
Jaguar	iPace	Full EV	90 kWh
Mitsubishi	Outlander PHEV	Hybrid	13.8 kWh
Volvo	XC90	Hybrid	12 kWh
Audi	A3 e-Tron	Hybrid	8.8 kWh

Again, as with ESS, there is a growing movement towards DIY EV's, with kits available on-line from sites like AliExpress at relatively low prices, making them an attractive proposition. It is unclear what standards these systems might be tested to.

The government is also planning to introduce a 'clean car rebate' scheme in 2021. The plan being to give discounts of up to $8k (for a new vehicle) to clean (low carbon emission) vehicles and apply a levy up to $3k to higher carbon emission vehicles. This is expected to increase the number of HEV's being imported into New Zealand.

There are currently no building consent requirements for installing EV charging systems in residential properties. Many of the incidents involving EV's discussed in Section 7.5 have occurred while the vehicle is on charge or parked.

It is recommended that parties such as the insurance industry, MBIE and homeowners should be advised on the potential risks associated with EV's being charged and parked in residential garages.

6.2 Small Batteries

The market for small batteries and individual cells is huge, literally millions in New Zealand alone. Again, it has been impossible to quantify the number of LI batteries in circulation due to the variety of uses and routes for importing, for example individual cells can be purchased in small or large volumes from retail outlets (e.g. Jaycar), on-line in New Zealand (e.g. TradeMe) or on-line from overseas (e.g. AliExpress).

6.2.1 Laptops

Where, in the past, laptop computers were the domain of businesses, they are now pervasive throughout society, in some cases people have both a personal laptop and a work laptop. Laptops are now also commonplace in schools and where schools do not have sufficient computing resources for all the students, they actively encourage the students to 'Bring Your Own Device' (BYOD).

There will also be a huge number of legacy machines. For example, BRANZ is a relatively small research organisation with around 120 employees and contractors but currently supports around 130 current and legacy laptop computers.

The size of laptop batteries varies by make and model, with most in the 40-65 Wh range. However, some machines, targeted at professionals on the move, have bigger batteries, up to 100-110 Wh capacity or an additional battery compartment in lieu of an optical drive.

6.2.2 Cell Phones and Tablets

A survey by Android Authority (AA) tracked 85 of the most popular cell phone makes and models over 5 years. The survey showed that the capacity of cell phone batteries is slowly increasing, from an average of 2,500mAh in 2013 to around 3,400mAh in 2018 [AA, 2018].

It should also be noted that charging rates are also increasing. Modern phones are able to 'fast-charge', in some cases at up to 100 W (Android Authority, 2019). Chargers and cables are often subject to physical abuse and/or damage which might then lead to an external ignition source.

Data from the 2018 Internet Survey Provider Survey by Statistics NZ (StatsNZ) show that in 2018, there were 4.96 million cellular devices with internet connections in use, an increase of 29% on 2017 [StatsNZ, 2018].

Based on the authors experience, it is likely that most people will have at least one old cell phone lying around the home or at work. This puts the number of cell phones in New Zealand closer to 10 million or more. A recent survey by the Royal Society of Chemistry (RSC) surveyed 2,353 people in the UK and found that 45% of those surveyed had at least 5 un-used devices (cell phones, laptops, smart TV, MP3 player or tablet) at home and 82% of those had no plan to re-cycle them (RSC, 2019).

6.2.3 Power Tools

Power tools have evolved. In the early days of rechargeable tools, manufacturers used Nickel-Cadmium (NiCad) powerpacks but they suffered from low capacity and 'memory effect' when charged, resulting in short lifespans in the commercial world.

Some manufacturers then moved to NiMH to increase power density. NiMH don't suffer from the same 'memory effect' as NiCad and therefore have a much longer service life.

Most battery-operated power tools these days are powered by LI and the capacity of the batteries is still growing at rapid rate. For example, Ryobi have a selection of battery sizes for the One+ range of 18 V power tools, 1.3 Ah, 1.5 Ah, 2.5 Ah, 4 Ah, 5 Ah, 6 Ah and most recently introduced, a 9 Ah (162 Wh) battery pack.

It is unknown how many power tool LI battery packs might be in use in New Zealand, but it is considered by the author that most households are likely to have at least one battery operated power tool. At 30 June 2018, a total of 25,464 individual licensed building practitioners (LBP's) were registered (BPB, 2018). It is considered by the author that most LBP's will have multiple battery-operated power tools to undertake their day-to-day building activities. StatsNZ record more than 130,000 trade workers in the construction industry, many of which would use battery-operated power tools too.

6.2.4 Power Banks

Power banks are becoming a popular way to extend the battery life of mobile devices. Charged via USB, they range in size with some claiming up to 30 Ah @ 5 V (150 Wh).

Of greater concern is power banks now being sold, that claim to be capable of jump starting a car. A standard car engine requires hundreds of amps to start the engine, this is normally supplied by the car battery which would normally be a lead-acid battery, specifically rated to deliver enough cold cranking amps (CCA) as specified by the car manufacturer.

Some of these jump starter power banks claim to be capable of delivering 150-300 A @ nominally 12 V (a standard lead-acid car battery is normally around 13.8 V) with alligator clamps attached to a dedicated connector. Four LI cells in series would provide 14.8 V nominally. However, even with some of the highest discharge capacity cells (20C @ 3.2 Ah) there would need to be at least 4 or 5 strings of 4 cells in parallel to deliver the required current. Most of these devices are not physically big enough to hold 20 3.2 Ah cells, which would lead the author to believe that the limited number of cells inside these devices are being discharged at a rate far higher than the cell manufacturer intended. This could lead to damage to the cells and increase the potential for thermal runaway, especially since having just been used to start a vehicle, it would have drained most of the power from the battery and it would likely need charging.

Additionally, the solenoid and starter motor are inductive loads. When the key is turned, a high current is drawn, initially by the solenoid, to connect the starter motor to the battery and then, by the starter motor itself, to turn the engine over. Once the engine starts, the key is released. The large magnetic fields built up in both the solenoid and the starter motor windings has to go somewhere. As the fields collapse, a large voltage spike is caused in the opposite direction to supply. This backward electro-motive force (back EMF) could achieve as much as 200 volts for a very short time period. Without sufficient suppression at the lithium battery, this would easily jump across the very thin insulator between the anode and cathode in the cell, potentially punching a small hole through it, leaving the cell open to a short circuit and thermal run-away.

Further work is required to determine the safety of LI based power banks when used to 'jump-start' vehicles.

6.2.5 E-Scooters and E-Bikes

E-Bikes capable of supplying more than 300 W must be registered with the New Zealand Transport Agency (NZTA) for use on public roads. NZTA data for e-bikes was analysed, but found to be incomplete, with few specifics around make, model and numbers registered. According to a Stuff.co.nz article in January 2018 (Stuff, 2018), there were 40,000 e-bikes in New Zealand, another 47,000 e-bikes and e-scooters were imported in 2018 (Stuff, 2019).

E-bike batteries are normally 36 V and range from 7 to 17 Ah (Bicycle Junction, 2019) meaning that e-bike batteries are at the top end of the small battery market, at between 252 and 612 Wh. Many have removable battery packs that users take inside to charge, others require the charger to be connected to the bike through an extension lead.

Across New Zealand, ignoring privately owned e-scooters, there are almost 4500 commercially operated e-scooters such as Lime, Flamingo and Uber, operating in Auckland, the Hutt Valley, Wellington and Christchurch.

There is no accurate data on the number of accidents occurring with e-scooters. 1545 injuries or deaths involving e-scooters were reported in the United States in 2018 (Business Insider, 2019). This number is likely to vastly under report the number of incidents where injuries don't occur but might result in mechanical damage to the e-scooter, which might compromise the safety of the battery.

Gen 2.5 Lime e-scooters have a 30 cell, 9.6 Ah battery pack built into them. Gen 3 Lime e-scooters (introduced in New Zealand in August 2019) have a much larger 50 cell, 15.9 Ah battery pack built into them. 'Juicers' (the members of the public who charge Lime scooters in return for payment) are encouraged to take home and charge as many scooters as they can find (ones below 20% during the day and any e-scooter after 9pm). This policy encourages 'juicers' to charge as many e-scooters as they can overnight, when they are likely to be sleeping and not monitoring the charging process for any anomalies that might occur as a result of any damage sustained during the day.

A Lime policy is on insuring those charging their e-scooters could not be found during the course of this study. Will insurers pay out on a home policy where someone has been charging e-scooters for financial reward?

It is recommended that the insurance industry should be consulted to determine if New Zealand residents are being exposed to potential risk of uninsured losses as a result of 'juicing' operations.

There are also a wide variety of e-bike and e-scooter build/conversion kits being sold on overseas websites like AliExpress. The New Zealand DIY culture is likely to drive an increase in the number of these cheap, low quality imports being brought in, where the source of the LI cells is unclear.

6.2.6 Vaping Devices

Vaping, or the use of e-cigarettes, is growing in response to a push to make New Zealand smoke free by 2025. The Ministry of Health (MoH) position statement says, *"The Ministry of Health considers vaping products have the potential to make a contribution to the Smokefree 2025 goal and could disrupt the significant inequities that are present."* (MoH, 2018). Founder of NZVapor, QJ Satchell, claims there are already over 200,000 vapers in New Zealand (Warhurst, 2019).

There are 550,000 smokers in New Zealand (MoH, 2018), so the market for these devices is substantial and although the MoH recommendations are aimed at encouraging smokers to quit by switching to vaping, there is evidence that the big tobacco companies are advertising vaping and vaping devices to non-smokers (McKenzie, 2019).

The heating coil used in the vaping device to turn the 'vape juice' into vapour to be inhaled varies from 0.5-3.0 ohms in resistance depending upon user preference. Generally, the devices use standard size LI cells (18650, 20700, 21700 or 26650). They might use a single cell or two cells in series. This means that the current draw from the battery can range from under an amp to ~15 amps depending upon configuration. If sub-standard cells are used, there is potential for these high drain devices to cause the cells to go into thermal runaway.

The BBC has reported in September 2019 that globally the number of vapers has risen from 7 million in 2011, to over 41 million in 2018 and is predicted to reach 55 million by 2021.

7. Global Incidents

More and more incidents around the world are being reported, relating to LI battery fires, as would be expected, with the growing use of LI batteries.

The latest high-profile incident is potentially one of the biggest 'loss of life' incidents to-date. It occurred in the early hours of 2nd September 2019, 34 passengers and crew died on the 75ft long 'Conception' dive boat, off the coast of California. Although the cause of the fire is still under investigation, the US Coast Guard has released a Safety Bulletin "asking the owners and operators of commercial boats to think about limiting the unsupervised charging of cellphones and other electronics that use lithium-ion batteries" (Andone, 2019).

Aircraft related incidents are also on the rise. The US Federal Aviation Authority (FAA) recently published a list of incidents recorded between 1991 and August 2019. The data identified 265 incidents over the period (either in the air, or on the ground within FAA jurisdiction). Early incidents included batteries that were not lithium ion although most are. However over half of those listed occurred in the last 3 years, with 47 and 49 being recorded in 2017 and 2018 respectively (FAA, 2019). This equates to almost an incident per week on aircraft in the US alone. This is also supported by reports from the Coalition of Airline Pilots Associations (CAPA) who are 'deeply concerned' (CAPA, 2019) about the issue.

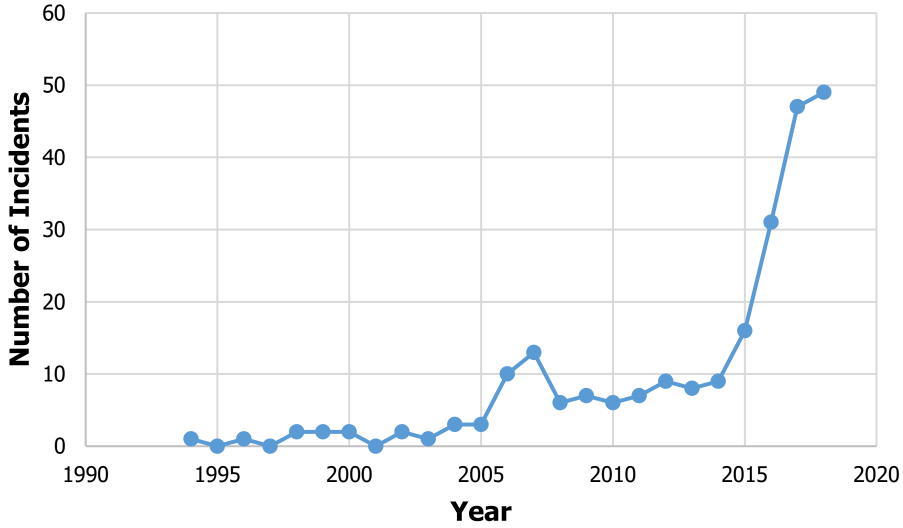

Figure 9. FAA Battery Related Incidents

However, a review of the data shows that prior to 2014, most incidents were ground events and the bulk of those were a result of poorly packaged batteries, not contained in a device. After 2015, there is a sharp rise in the number of incidents occurring in the air, these primarily relate to cell phones/tablets (24), power banks (19), e-cigarettes (14) and to a much lesser extent, laptops (7).

Even in the aviation industry, which is considered one of the most safety conscious, highly regulated industries, aircraft themselves are not immune to the problem. In 2013, the Boeing 787 (B787) Dreamliner aircraft was grounded in its first year of operations after a number of aircraft had problems connected with the new LI batteries used in the aircraft (FAA,2013).

- 7 January 2013 – A battery fire was reported in a Japan Air Lines B787 at Boston Airport.
- 9 January 2013 – United Airlines reported a problem with wiring in the vicinity of the battery in one of its six B787 aircraft.
- 16 January 2013 – An All Nippon Airways B787 performed an emergency landing at Takamatsu Airport after a 'smoke' warning in the battery compartment.

After modifications, the aircraft were cleared to fly again but in January 2014, Japan Airlines ground crew discovered smoke coming from the main batteries of a B787, 2 hours before an aircraft was due to depart and in November 2017 a United Airlines B787 experienced a battery overheating on approach to Charles de Gaulle airport.

Incidents are not restricted to LI battery users, there have been a number of incidents at plants manufacturing cells:

- November 1995 – A Sony battery factory fire destroyed ~3 million cells and damaged 7,000 m^2 of the factory in Japan.
- August 1997 – A Matsushita Battery Industries factory fire destroyer ~1.22 million cells and burned 1,700 m2 of the factory in Japan. Buildings within 175 m radius were damaged.
- August 2008 – A fire destroyed a production area and warehouse at Batterie-Montage-Zentrum in Germany.
- September 2008 – A very large format (6 ft by 8 ft) battery, undergoing testing, caught fire in Pawcatuck in the US, triggering an evacuation of the village.

7.1 Cell Phones

There have been fire incidents relating to cell phones or cell phone chargers reported all over the globe, most notably the Samsung Note 7. Released on 19 August 2016, sales were suspended on 2 September 2016 after a number of incidents of the phone overheating and catching fire. After an initial recall on 12 September 2016, an alternative battery was fitted and firmware updated to limit charging capacity. However, in early October 2016, a several replacement Note 7's also caught fire and subsequently, Samsung issued a full recall, suspending sales of the Note 7 on 10 October 2016 (Samuelson, 2016). Not all Note 7 users wanted to surrender their devices, so over the following months, Samsung instructed network operators to push out updates to restrict the use of the devices and eventually block them from connecting to the cellular networks by blacklisting the IMEI's (Amadeo, 2016).

It has not been possible to quantify how many incidents have occurred globally. However, incidents have been reported in the press all over the world, including a number of deaths caused by cell phones exploding in close proximity to the victim.

FAA data shows that since 2012, there have been 24 incidents relating to cell phones in the air and a further 9 incidents on the ground. A number of the incidents in the air were caused by cell phones being trapped in the reclining mechanism of aircraft seats, causing physical damage to the phone prior to ignition.

Cell phones are prone to physical abuse, many get dropped onto hard surfaces, get crushed in handbags or bent in a pocket. Apple is still the subject of a lawsuit relating to the 2014 iPhone 6 'bend-gate'. Any physical stresses to the case can be transferred to the battery and potentially result in a failure of the battery.

7.2 Laptops

In June 2019, Apple issued a worldwide recall notice for certain 15-Inch MacBook Pro laptops, stating that *"in a limited number of older generation 15-Inch MacBook Pro units, the battery may overheat and pose a fire safety risk."* The affected units were sold between September 2015 and February 2017. Apple does not say how many units are believed to be affected but their website has a serial number search for eligibility and recommends not using the device until the battery is replaced (Apple, 2019).

In January 2018, HP issued a worldwide recall notice for a range of notebook and mobile workstations, this was extended in January 2019 to include additional models. The recall states that *"The batteries have the potential to overheat, posing a fire and burn hazard to customers."* Table 4 lists the models shipped with affected batteries, as well as model that although not directly affected, could by the purchase of replacement batteries.

Table 4. HP Worldwide Recall

Models shipped with affected batteries	Models that may have received replacement batteries affected
HP 11-f100 Notebook PC series	HP ENVY 15-ae100 Notebook PC
HP 11-f000 Notebook PC series	HP mt20 Mobile Thin Client
HP 11-f000 Notebook PC series (Touch)	HP mt21 Mobile Thin Client
HP ENVY m6-p100 Notebook PC	HP mt31 Mobile Thin Client
HP ENVY m6-p100 Notebook PC (Touch)	HP ProBook 430 G5 Notebook PC
HP ENVY m6-p000 Notebook PC	HP ProBook 440 G5 Notebook PC
HP ENVY m6-p000 Notebook PC (Touch)	HP ProBook 450 G5 Notebook PC
HP Pavilion 15-dq0000 x360 Convertible PC	HP ProBook 455 G5 Notebook PC
HP Pavilion 15-bk000 x360 Convertible PC	HP ProBook 470 G5 Notebook PC
HP ProBook 430 G4 Notebook PC	
HP ProBook 440 G4 Notebook PC	
HP ProBook 450 G4 Notebook PC	
HP ProBook 455 G4 Notebook PC	
HP ProBook 470 G4 Notebook PC	
HP ProBook 640 G2 Notebook PC	
HP ProBook 640 G3 Notebook PC	
HP ProBook 645 G3 Notebook PC	
HP ProBook 645 G2 Notebook PC	
HP ProBook 650 G2 Notebook PC	
HP ProBook 650 G3 Notebook PC	
HP ProBook 650 G3 Quad Core Notebook PC	
HP ProBook 655 G3 Notebook PC	
HP ProBook 655 G2 Notebook PC	
HP x360 310 G2 EE Convertible PC	
HP x360 310 G2 Convertible PC	
HP ZBook 17 G3 Mobile Workstation	
HP ZBook 17 G4 Mobile Workstation	
HP ZBook Studio G3 Mobile Workstation	
HP ZBook Studio G4 Mobile Workstation	

Again, it is not known exactly how many units are involved in the recall, or indeed if all of the affected units have been replaced.

In August 2006, Dell recalled 4.1 million of its laptop batteries due to concerns about them overheating and catching fire. The batteries were manufactured by Sony and used in laptops by Apple, Dell, Lenovo, Fujitsu and Toshiba who all issued product recalls in the wake of the problem.

FAA data would point to a relatively low incidence of laptops catching fire, with 10 incidents in the air since 1998 and a further 15 on the ground. Many of the ground related incidents have involved laptops as cargo that have been dropped during transit.

7.3 Vaping Devices

As discussed earlier, the global market for vaping devices is huge, with over 41 million users worldwide.

There have been a number of widely publicised events caught on CCTV, where vaping devices (or spare batteries) have exploded without warning in the pocket of the user, leaving them with extensive partial and full thickness burns.

There have also been cases recorded, where vaping devices have exploded while in-use, causing severe facial trauma. In April 2016 an Orange County man lost his eye as a result of debris from an exploding e-cigarette battery. In March 2018, an e-cigarette exploded in the mouth of a 17-year-old boy, resulting in a fractured lower jaw (with a 2 cm section of jaw missing) and multiple lost teeth, requiring reconstructive surgery.

The US Federal Emergency Management Agency (FEMA) released a report on vaping device incidents in 2017. It found reports of 195 incidents of e-cigarettes exploding or catching fire. In 68% of those incidents (133), acute injuries were reported. The device was either in-use or in a pocket in 121 cases, with another 48 being reported while being charged (FEMA, 2017).

A George Mason University study (published in Tobacco Control) suggests that in the US, between 2015 and 2017, there were 2,035 visits to emergency departments (ED) as a result of e-cigarettes exploding (Rossheim et al., 2018).

FAA data shows 14 incidents in the air since 2014 and a further 30 incidents on the ground (FAA, 2019).

It is the authors opinion that since those in lower socio-economic areas in the US are less likely to have medical insurance, making them less likely to present to an ED for minor injuries. It is also the authors opinion, that where no injury is sustained, there is a high probability that incidents would go unreported. These two factors mean that the number of incidents of vaping devices exploding or catching fire is likely to be far higher than reported.

7.4 Waste Sites and Rubbish Trucks

Fires at waste (refuse and/or recycling) sites and in rubbish trucks are commonplace, generally caused by people disposing of aerosols or chemicals that should go through hazardous waste disposal rather than normal refuse collection. However over recent years, the number of incidents being caused by LI batteries being disposed of in the normal waste streams have increased.

LI batteries are not universally considered to be hazardous waste. For instance, Panasonic state on their Product Information Sheet that *"All Panasonic Lithium ion batteries are classified by the federal government as non-hazardous and are safe for disposal in the normal municipal waste stream"* (Panasonic, 2018).

In March 2018, a fire started by a discarded LI battery in a recycling facility in Queens, NY required 200 fire-fighters to bring under control (Waste 360, 2018).

An article in USA Today in May 2018 claimed that *"Last year, 65% of waste facilities fires in California began with lithium-ion batteries."* (Weise, 2018). The article also cited the incident above, in Queens, a recycling plant fire in Indianapolis, and an explosion inside a NY city garbage truck.

Bosch and GS Yuasa Corp. aim to sell a lithium ion battery that can deliver twice the energy density for half the production cost, by 2020 (Greimel, 2013). "The less expensive and more powerful they get, the more issues the waste and recycling industry will face, as the number of lithium-ion batteries explode from today's baseline." (Fogelman, 2017).

The Japan Containers and Packaging Recycling Association recorded 128 incidents in the 2018 fiscal year, more than double that in 2017 and four times as many as 2013 (Japan News, 2019).

It is recommended that there should be a 'public education' programme around the safe disposal or recycling of old lithium-ion batteries.

7.5 Hybrid & Electric Vehicles

Questions have been raised around the safety of Hybrid & Electric Vehicles (HEV's), although this does not appear to be affecting vehicle sales, for example, Tesla delivered 95,200 vehicles in Q2 2019 (Tesla, 2019a) and continues to outsell its EV competitors (Chang, 2019).

The Chevrolet Volt was one of the first vehicles to be investigated by the National Highway Traffic Safety Administration (NHTSA), after a vehicle used for 'crash-testing' caught fire 3 weeks after the testing was undertaken. Chevrolet made modifications to the vehicle following the investigation. However, it did highlight the problem of lithium battery stability after an incident and the fact that it can take a prolonged period of time for the cells to experience a thermal runaway event. For example, a Tesla Model X caught fire after a fatal crash on a California freeway on March 23rd, 2018. It was extinguished by the fire department. Tesla engineers then removed one quarter of its power cells before it was deemed safe to be towed away. However, it re-ignited twice more in the following 24 hours and again six days later (Levin, 2018).

There have been a number of very high-profile incidents involving Tesla cars catching fire. However, most of these have involved a collision prior to the car catching fire. Those that have not involved a collision caught fire while in-use, on charge and also while parked and not in-use. In January 2016, a Model S in Norway caught fire whilst on charge, although the fire is thought to have originated at a short-circuit in a junction box, not the vehicle battery (Hattrem, 2016). In August 2016, a Model S spontaneously caught fire during a test-drive in Biarritz in France. The driver and passengers were able to safely exit the vehicle after a dashboard warning (King, 2016). More recently, in April 2019 a Model S in a parking garage in Shanghai caught fire for no apparent reason, the fire spread to 5 other vehicles before it was extinguished

(Rapier, 2019). 16 incidents (Wikipedia, 2019) have been reported where Tesla vehicles have caught fire (including high-speed collision events), this equates to 0.000022% of Tesla vehicle sales.

Other incidents have involved Mitsubishi i-MiEV and Outlander PHEV, Nissan Leaf, VW e-Golf, Porsche Panamera E-Hybrid and Hyundai Kona Electric.

An article on Business Insider in Australia points out that in the US alone, about 150,000 conventional combustion engine cars catch fire each year (about 17 every hour), killing on average 209 people a year, as reported by the National Fire Protection Agency (NFPA). Tesla CEO, Elon Musk, drew on data from the NFPA when he stated that "*Americans drive about 3 trillion miles per year according to the Department of Transportation. That equates to 1 vehicle fire for every 20 million miles driven, compared to 1 fire in over 100 million miles for Tesla."*

Incidents following salt-water ingress are of concern to the New Zealand market, given the large recreational 'boatie' population. It is the authors opinion that there is likely to be an increase in the number of HEV's being used to put pleasure craft in and out of the water. Reports after Hurricane Sandy in October 2012 included 3 Toyota Prius incidents (1 caught fire, 2 smouldered) and 16 Fisker Karmas incidents (although the Fisker incidents were attributed to the 12-volt power system, not the high voltage lithium ion battery packs). In May 2019, a 2018 Mitsubishi Outlander P-HEV caught fire after immersion in salt-water, when it was being used to haul a boat out of the water at Port Moody boat ramp (Little, 2019).

7.6 Energy Storage Systems

There have been a number of large-scale, network based, ESS fires around the world.

7.6.1 Engie Electrabel

In November 2017, a fire occurred at the Engie Energy Storage Park in Drogenbos, Belgium. The Engie Electrabel test site was being used to test ESS based frequency containment reserve services from four different manufacturers, Ineo Scle Sfe, Alfen, GE and Younicos, each providing 6 MW capacity.

The fire broke out during commissioning, none of the systems were connected to the grid at the time. A 1 MW Ineo battery container was a total loss, neighbouring containers by GE and Alfen suffered light (repairable) damage as a result of the fire.

The facility was fully equipped with fire detection and extinguishing systems, although these failed to extinguish the fire (Deign, 2017).

7.6.2 Arizona Public Service Incidents

In November 2012 Arizona Public Services (APS) had a fire at McMillan Mesa, a 1.5 MW federally funded pilot facility (where LI batteries were being tested) caught fire causing damage to the $3m installation. The cause of the fire is unknown, but APS worked with the battery manufacturer, Electrovaya Inc. (Ferguson, 2013), to learn from the incident. Improvements included improved ventilation between cabinets, incorporating 24/7 monitoring and the ability to send remote alarms.

APS now supports 3 large-scale battery systems in their network for solar collection, voltage regulation and power quality services and announced plans to add a further 850 MW of battery by 2025 (APS, 2019a).

Table 5. APS ESS Facilities

Location	Capacity	In-Service Date
Buckeye, Arizona	2 MW max / 2 MWh total	March 2017
McMicken, Arizona	2 MW max / 2 MWh total	March 2017
Punkin Center, Arizona	2 MW max / 8 MWh total	March 2018

A second incident occurred at the APS McMicken facility in Surprise, Arizona in April 2019. The cause of the fire and subsequent explosion are still under investigation. The systems consisted of 27 rack, each containing 14 modules of LI batteries (APS, 2019b). Eight first responders were injured when heavy metal doors were blown off their hinges by the force of the explosion inside. One had critical injuries, two were serious and the remaining five were released from hospital. Injuries included, both thermal and chemical burns, multiple fractures, lacerations and a collapsed lung (Klock, 2019).

7.6.3 Korean Incidents

Korea has adopted very ambitious goals for clean energy usage, with individuals, companies and other organisations installing 1,253 ESS across the country. However, they have had a number of significant fires.

In December 2018, an ESS installed at a cement plant in Jecheon caught fire causing $3.6m USD in damages to the plant. It was the 15th ESS fire in 2018 and occurred as the Korean Ministry of Trade, Industry and Energy were undertaking inspections of all ESS facilities. The installation was setup by LG Chem, one of the top 3 LI cell manufacturers (Hyun-woo, 2018).

Figure 10. A fire engulfs an ESS at a cement plant in Jecheon, North Chungcheong Province, Korea

Source: North Chungcheong Province Fire Service Headquarters

As of June 2019, 23 fires have been reported in Korean ESS facilities. The Korean authorities conducted an investigation into the fires and determined that they were not caused by faulty cells but found *"electric shocks caused by faulty battery management, system control or battery protection systems and faulty installation practises"* (Colthorpe, 2019).

8. Reported Incidents in New Zealand

Energy Safety NZ (ESNZ) is a part of WorkSafe New Zealand and is the electrical and gas regulator in New Zealand.

Data was provided by ESNZ on all reported incidents relating to batteries and chargers between 2009 and April 2019. This data was filtered to identify only incidents relating to lithium-ion batteries and chargers (ESNZ, 2019).

The data was analysed, to look at both the general trend, as well as looking at the risks around particular recurring items, the vast majority of which are being charged at the time of the incident.

The trend in incidents relating lithium-ion batteries is growing at a significant rate, as can be seen below in Figure 11.

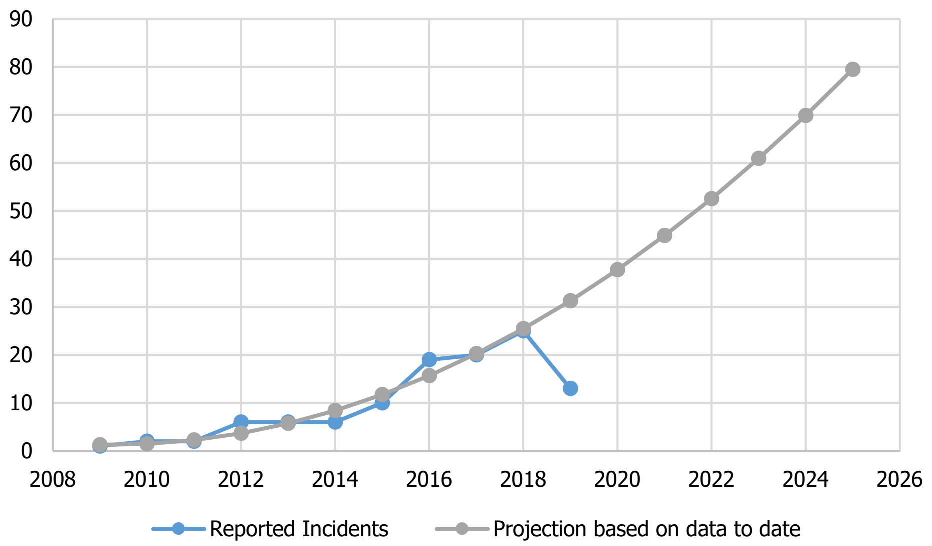

Figure 11. Battery related incidents in New Zealand

It should be noted that the drop in 2019 is due to the fact that data was only available to April. If the data was pro-rata for the year, it would exceed the current trend line. If the current growth trend continues, by 2025 there could be as many as 80 incidents reported per year. It is the opinion of the author (from experience) that most incidents involving lithium batteries that do not require the intervention of FENZ and even some that do, are probably not being reported to ESNZ, meaning that the size of the problem could be bigger than perceived.

There are some notable examples where data appears to be missing from the ESNZ data.

In April 2015, a fire was reported in the Nelson Mail (Pullar & Malone, 2015). The article entitled "Batteries blamed for fire that destroyed Stoke home" stated that the fire investigator believed that most likely cause of the blaze was an LI battery left charging in the garage, located on the middle floor of a 3-storey home. This fire was not included in the ESNZ data.

In February 2018 FENZ were called out to the Rocket Lab facility in south Auckland. Smoke was reported coming from 2 of the large batteries used in the Electron rocket. Although no-one was hurt, this is a concerning incident given that each Electron rocket contains 1 MW of battery power (BatteryBro, 2015). Again, this incident was not included in the ESNZ data.

8.1 Large Batteries

To-date there have not been any reported incidents involving commercial large-scale batteries (ESS or HEV) in New Zealand. Evidence from around the world would suggest it is likely a matter of time before an incident does occur.

A large 24 V lithium battery (3.2 kWh) destined for a super yacht did catch fire in storage in December 2018 but does appear to be an isolated incident.

There has been an incident of significant concern in Balclutha, in January 2019, where a DIY ESS built out of old laptop batteries (18650 cells) was being used to supply power to kitchen appliances. The only protection was provided by 5 amp fuses. There was no BMS or charging protection of any kind. The fire did a significant amount of damage to the kitchen but could have been far more extensive if the occupier had not been home at the time, to alert the emergency services.

8.2 Small Batteries

8.2.1 Cell Phones

There are no reported incidents in New Zealand relating to cell phone batteries before 2013, however from 2014 there have been 17, with 11 of those reported in the past 2 years (2017/18). If these incidents are considered to be related to general failures (either in the battery or charger) then it could be surmised that with an increase in the number of cell phones in use, then the number of incidents might increase accordingly. If on the other hand, some of the faults could be as a result of design flaws, such as the iPhone 6 or the Samsung Note7, then it could be surmised that as these get fixed, the number of incidents might remain the same or even reduce. It is the author's opinion that there are likely to be multiple factors and we are likely to see a short-term growth in incidents as cell phones age, with a gradual rate reduction as new designs remove existing flaws or move to more stable battery chemistries, but the quantity of phones in existence continues to rise.

8.2.2 Laptops

There have been 10 incidents reported in New Zealand, since 2013, involving laptops. Most incidents involve batteries overheating, rather than catching fire. However, an incident in April 2015 injured the owner, when the 3rd party non-OEM battery exploded. The laptop, purchased 2nd hand and owned for over 4 years, was being charged, when the owner noticed it overheat and begin to smoke. In the process of transferring the laptop to the kitchen sink, the battery exploded in his hand causing partial thickness burns to the base of his fore-finger and flash burns to his neck.

As with other small battery fires, it is considered by the author that it is likely that fires controlled or extinguished without the assistance of FENZ are also unlikely to be reported to Energy Safety and therefore would indicate that the number of incidents is likely higher than reported.

There have been 11 recalls of laptop computers or batteries since 2014 (Recalls, 2019). They indicate potential overheating problems and fire risk with the LI battery pack, details are shown in Table 6 below.

Table 6. Laptop Recalls in New Zealand

Manufacturer	Date of Recall	Models Affected
Lenovo	9/4/2014	T510, X201, X201s Edge 13, laptops sold between October 2010 and April 2011.
Sony	1/5/2014	VAIO Fit11A
Toshiba	29/1/2016	Portege, Satellite, Satellite Pro, Tecra R840 laptops sold between June 2011 and September 2015.
Panasonic	18/2/2016	CF-VZSU61U sold in 2012
Toshiba	21/11/2016	Extended January recall to include Satellite models sold between July 2013 and November 2016
Sony	25/11/2016	The effected battery model (VGP-BPS26) may have been sold with SVE15137CGP, SVE15138CGB, SVE15138CGS, SVE15138CGW and repaired models between December 2012 and September 2013.
HP	21/2/2017	Batteries sold with Compaq, HP ProBook, HP ENVY, Compaq Presario and HP Pavilion laptop computers and any batteries with serial number beginning 6BZLU,6CGFK, 6CGFQ, 6CZMB, 6DEMA, 6DEMH, 6EBVA or 6DGAL, sold between March 2013 and August 2016.
Lenovo	12/2/2018	ThinkPad X1 Carbon 5th Generation laptops sold between December 2016 and October 2017.
HP	22/2/2018	Internal batteries fitted to ProBook, x360 310 G2, ENVY, Pavilion x360 and Zbook laptops and workstations sold between January 2015 and December 2018
Panasonic	5/7/2018	CF-AX Series, CF-C2 Series and CF-SX Series Toughbooks sold between April 2013 and March 2016.
Apple	24/6/2019	MacBook Pro (Retina, 15-inch, mid 2015 model) sold between September 2015 and February 2017.

8.2.3 Vaping Devices

Although the evidence around the world would point to a high number of incidents involving vaping devices (FAA, 2019), only three incidents have been reported to ESNZ, with 2 of those occurring in 2017. It is the opinion of the author that unless there is a fire, or injury involved, it is unlikely that incidents are being reported to ESNZ.

8.2.4 E-bikes / Scooters / Hoverboards

The number of incidents involving E-bikes, E-scooter and Hoverboards is relatively low compared with other uses of LI batteries. However, the number of these type of devices is increasing rapidly, with both commercial and DIY variants. 2018 saw a spike in the number of incidents, with 5 reported to ESNZ, with most occurring during charging.

A recall was issued for Foldable Electric Scooters, sold by a TradeMe store between September 2017 and March 2018. Although not directly related to the LI battery, an electrical fault posed a fire risk (Recall, 2019).

8.2.5 Powerbanks

There are a significant number of incidents occurring with powerbank devices. Of particular concern are powerbank devices that are being advertised for 'jump starting' cars.

Since 2013 there have been 16 incidents involving powerbank type devices. Of those, since 2017, there have been 8 involving 'jump start' type devices, all but one of these were while the device was being charged. The incident reports only determined that the units were being charged. The more important question to ask based on section 6.2.4 would be "whether the device had been used previously to start a car or not". If this is the case, should these items be deemed to be a consumable (use once and dispose of appropriately).

8.2.6 Toys

Li battery toys have been involved in a wide range of incidents. However, the most notable are those where the battery does not have a BMS.

Radio controlled (RC) toys feature this type of battery and not surprisingly, they are a common cause of fires, with 12 incident involving batteries for RC toys / Drones on charge in the past 10 years, 7 of those since 2016.

8.2.7 Tools

Tools feature as quite a large group, including 28 incidents. Incidents involving head torches (of which, there have been 7) have been grouped together with cordless power-tools. The problem with power tools would appear to stem from the fact they are generally left on charge for extended periods. For example, at the end of the workday, the batteries might be put on charge and left over-night to be ready for the next day's work. Five incidents have been recorded where either the battery has overheated during or shortly after charging. Of particular concern are three incidents involving Milwaukee power tools in the past year.

9. Standards

9.1 New Zealand

There are no New Zealand standards that relate directly to LI batteries. However this is not surprising, since New Zealand is not a manufacturing centre for LI batteries.

There is a current draft standard AS/NZS 5139:2019, Electrical Installations – Safety of battery systems for use with power conversion equipment. Of particular concern in the draft standard is Table 3.1 (which identifies hazards associated with different battery types) that states "Lithium ion pre-assembled battery system equipment or pre-assembled integrated BESS equipment conforming to the *Best Practice Guide: battery storage equipment — Electrical Safety Requirements* are N/A" for fire hazard, if not, they are a class 1 (self-sustaining) fire hazard (Joint Australian/New Zealand Standards, 2019). A number of incidents involving very reputable ESS manufacturers have shown the ability for an ESS to catch fire, as a result of an internal fault, and fire to propagate beyond the confines of the ESS.

9.2 International

This literature review has not undertaken an exhaustive search of worldwide standards.

Different jurisdictions around the world have standards for battery operated equipment and storage systems. They mostly follow a similar approach of cell level testing, battery level testing and ultimately in some cases, system level testing.

In the United States (US), Underwriter Laboratories (UL) developed UL 1642 for cell level testing, UL 2054 for battery level testing and is globally recognised and accepted. UL 9540 has been developed specifically to provide system level testing of ESS. UL 9540A is a test method for evaluating thermal runaway fire propagation in battery ESS, it is not currently a standard, but is referenced in the National Fire Protection Association (NFPA) draft standard NFPA 855: Standard for the installation of Stationary Energy Storage Systems.

For European markets, IEC 61223-2:2017 - Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary lithium cells, and for batteries made from them, for use in portable applications - Part 2: Lithium systems, covers both cell level and battery level testing and again is becoming globally recognised and accepted.

10. New Zealand Building Code

There are currently very limited provisions in the New Zealand Building Code (NZBC) to restrict the installation of battery and charging installations.

Code clause C2 – Prevention of fire occurring, is aimed at ensuring that appliances (which are hot in normal use) are not able to cause ignition of surrounding materials, by restricting the maximum surface temperature. This is not intended to cover fault conditions. Under normal (non-fault) conditions, LI batteries pose no higher risk than any other appliance.

Code clause G9 – Electricity, has a clear objective in G9.1(a) to ensure that "the electrical installation has safeguards against outbreak of fire and personal injury". The performance requirement G9.3.1(e) requires that "the electrical installation shall incorporate a system to: … Protect building elements from risk of ignition, impairment of their physical or mechanical properties, or function, due to temperature increases resulting from heat transfer or electric arc".

Discussions with building consent officers in Porirua City Council and Auckland City Council would indicate that, although a consent would be required to install a residential solar power generation system, this is for structural purposes (i.e. to meet Clause B1 of the building code). There would be no building consent requirement from the councils for installation of an ESS or EV charging station. The only requirement is from an electrical safety perspective. The installation should be installed in accordance with AS/NZS 3000:2018, by a qualified electrician.

It is recommended that the installation of LI battery ESS or EV charging station should require a building consent to ensure the installation meets the requirements of NZBC clause G9.

Further work is required to provide guidance on how to prevent spread of fire in the event of an ESS thermal run-away failure scenario.

Further work is required to provide guidance on prevention of spread of fire from garages as a result of EV or charger faults.

11. Recommendations and further work

A literature review was undertaken to identify the potential fire hazards associated with LI batteries and to inform FENZ of potential actions that could be taken to address the fire threat posed by these batteries. The study looked at incidents in New Zealand, as well as overseas and proposes the following recommendations for consideration by the sector:

1. All LI cells should be accurately labelled, to include the parameters required for safe operation. As a minimum, the cell voltage, maximum charging rate and maximum discharge rate.
2. A 'public education' programme should be developed covering:
    a. Safe use, disposal and recycling of old LI batteries,
    b. Correct charging of LI batteries,
    c. The risks of importing and using counterfeit LI batteries,
    d. Contacting Trading Standards or the Commerce Commission when faced with counterfeit batteries, or false claims around cell capacity.
    e. the potential risks associated with EV's being charged and parked in residential garages.
3. The installation of LI battery ESS or EV charging stations should require a building consent to ensure the installation meets the existing requirements of NZBC clause G9.
4. The insurance industry should be advised of the following potential risks:
    a. EV's being charged and parked in residential garages,
    b. The potential risk of losses as a result of 'juicing' operations.

This literature review has also identified the following areas where further research is needed:

5. Quantification of the joule effect when measuring HRR from LI cells during combustion.
6. An assessment of the risks to fire fighters, fire investigators and anyone else involved in the clean-up following an LI battery fire, including thermal, chemical and re-ignition risk. This risk may extend to insurance assessors, tradesmen and occupants.
7. The safety of LI based power banks when used to 'jump-start' vehicles.
8. Guidance on how to prevent spread of fire in the event of an ESS or EV thermal run-away failure scenario, or EV charger fault.

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