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Lithium battery recycling in Australia

Current status and opportunities for developing a new industry

A CSIRO Report

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Executive summary

Australian lithium ion battery (LIB) waste is growing at a rate of over 20 % per annum as a direct response to the increasing demand and uptake of portable and rechargeable electronic equipment and electric vehicles. In 2016, 3,300 tonnes of LIB waste was generated but only 2 % of this was collected and exported for offshore recycling. LIB waste generation is forecasted to grow to between 100,000 to 188,000 tonnes by 2036. Unfortunately, the majority of Australian LIB waste is disposed of in landfill, which has undesirable environmental and human health implications.

Given Australia's historically poor LIB collection, combined with offshore recycling and landfilling of this waste, this constitutes a future (2036) economic loss to the Australian economy due to the estimated potential recoverable value of between AUD $813 million and $3 billion based on current day commodity prices. LIB waste contains significant valuable resources like cobalt, lithium, base and other metals and graphite that could be recovered domestically and reused for new products.

Australia suffers from the often quoted 'tyranny of distance' to markets and a distributed population. The low battery recycling collection rates constitute a missed opportunity to both capture and add value to a waste stream. Recent disruptions to the recycling sector in Australia following the China waste ban have not affected the LIB recycling sector markets. However, the fire risk presented by end-of-life LIB has resulted in an international shipping company banning transport of this waste stream. This action poses a risk to Australia's reliance on export for end-of-life LIB. It is therefore timely to review the challenges and opportunities associated with LIB waste and determine if it is a strategic resource opportunity for Australia.

There is significant potential for targeted research to help realise Australia's opportunity to extract value from LIB waste. The Australian research community, in partnership with industry and governments can play a role in realising this opportunity and catalysing a new industry which in turn creates new jobs for Australia. Through the thorough desktop review and engagement of LIB battery recycling stakeholders, the following observations can be made to support the development of a domestic recycling industry in Australia.

Key Finding 1: Dedicated product stewardship programs and consumer education drives recycling and resource recovery from LIB

The lack of an appropriate product stewardship program and consumer awareness regarding recycling options for LIB are key issues that must be addressed in order to increase Australia's LIB collection rate. The current low collection rate of 2 % is reportedly limiting confidence and investment by industry into recycling infrastructure. General waste collection, transfer and management costs in Australia are costly due to large freighting distances between major population centres, without the additional impact of segregation of specialised waste streams such as LIB wastes. Introduction of a product stewardship scheme would enable rapid expansion and investment required for an expanding waste stream. Simultaneously, a targeted consumer awareness campaign and education program would help support investment in recycling processes and technology. Included in a consumer awareness campaign is to advertise existing collection sites and work towards new collection points by working with a range of OEMs, retailers and recyclers. Best practice recycling consumer guides for a range of key product ranges, such as handheld LIB, household energy storage products and EVs, would also support this effort. An education campaign also supports existing and potential future State and Territory battery landfill bans.

Key Finding 2: A safe and successful LIB recycling industry can be developed by addressing critical information gaps

Participants reported industry information gaps in best practice guides for standards regulating reuse of LIB, end-of-life transport, and recycling of LIB. Desirable information to support a successful industry included economic modelling, life cycle assessment for LIB reuse and recycling technology assessments. The collection of this information will support the safe development of an Australian LIB processing and recycling industry.

Key Finding 3: A need to identify technology processing options for the Australian context

Investment into recycling technology suitable for Australian conditions takes a modern approach to recycling. This requires the right technology and business models for an Australian context. Australia's distributed population is suitable for potential deployment of mobile processing technology. Alternatively, large scale LIB processing could also be feasible if key information and data gaps and economic modelling can be addressed. There would be a number of technical challenges that would require further research and development for both options, and this creates the potential for the development of innovative technology for the Australian LIB recycling industry. Participants suggested Australia has the potential to become a recycling hub with feedstock sourced from neighbouring countries such as New Zealand. This would further secure supply, improve economic feasibility and supports either large-scale or small-scale processing options.

Key Finding 4: An onshore, local LIB recycling industry is economically and environmentally achievable

There are strong economic and environmental drivers for Australia to manage LIB waste onshore. In this context, dedicated policies, regulations, standards and certifications relating to LIB and their waste will support technology development and industry investment in LIB recycling. Australia can view international examples such as those in the European Union and see how their existing policies, regulations and resource recovery targets have driven innovation and technology development. From this, appropriate changes can be made to provide maximum support for the Australian battery recycling landscape.

Key Finding 5: Creation of standards and industry best practice guides for LIB recycling

Dedicated standards surrounding labelling, safety, transport, discharge and processing were identified by stakeholders as key drivers for the success of the industry. Current standards need to be modified where applicable to cover LIB recycling and where required new standards would need to be written and adopted. In the interim, industry best practice guides will enable the industry to adopt new or modified standards and create a smoother transition to a new safe and environmentally sound LIB recycling process.

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Abbreviations

ABRI	Australian Battery Recycling Initiative
AMEC	Australian Mining Executive Council
AMTA	Australian Mobile Telecommunications Association
CEC	Clean Energy Council
CSIRO	Commonwealth Scientific and Industrial Research Organisation
EU	European Union
EV	Electric vehicle
e-waste	Electronic waste
FCAI	Federal Chamber of Automotive Industries
GW	Gigawatts
GWh	Gigawatt hours
HEV	Hybrid electric vehicle
IATA	International Air Transport Association
LCA	Life cycle assessment
LCE	Lithium carbonate equivalent
LCO	Lithium cobalt oxide
LIB	Lithium ion battery
LFP	Lithium iron phosphate
LMO	Lithium manganese oxide
LNO	Lithium nickel oxide
MW	Megawatts
MWh	Megawatt hours

NMC	Lithium nickel manganese cobalt oxide
NTCRS	National Television and Computer Recycling Scheme
OEM	Original equipment manufacturer
PHEV	Plug-in hybrid electric vehicle
USGS	United States Geological Survey

1 Introduction

This study was aimed at defining the current landscape of lithium battery recycling in Australia, and identifying the challenges and opportunities related to potential onshore processing of these wastes. The majority of existing recycling schemes rely on scrap metal recyclers to break down the waste for export as there is no dedicated infrastructure or technology to recover the value from the waste. This constitutes a missed opportunity for Australia to benefit economically, environmentally and socially. This research will help to shape the developing landscape of recycling and resource recovery in Australia, as well as identify strategic resources and potential economic gain from further development of the industry.

This report provides results from in-depth interviews conducted with six key stakeholders associated with the Australian LIB recycling sector. While the count of interviews is small, it is important to recognise that the Australian LIB recycling sector is also small, and the interviews captured 43 % of the LIB recycling and collection industry. Interview data is reported using the PESTLE (Political, Economic, Social, Technical, Environmental and Legal) categories. However, to counter for the low sample size, these data have been combined with a literature review and knowledge gained from attending industry events and academic conferences over the previous 12-24 months.

This report is structured into four sections. First, we review LIB market demand and the valuable resources contained within LIB waste. The second section summarises various product types, recycling process and recycling rates. The third section reports key findings from stakeholder interviews and the fourth section concludes with key observations.

The goal of this report was to synthesise information about this important resource stream to stimulate debate, focus action and ultimately support a broad range of industry, government and academic stakeholders to come together and invest in activities that support domestic processing of the LIB waste stream in Australia. The aim is for this research to contribute to the developing landscape of LIB recycling and resource recovery in Australia.

Part I

Lithium batteries: an emerging problem waste for Australia

Overview, specifications, value, resources demand and fate

2 General introduction to batteries and lithium batteries

2.1 An introduction to batteries

Batteries are energy storage devices which convert stored chemical energy into electrical energy. Batteries use chemical compounds which can either liberate or accept electrons or ions within an electrochemical cell during a redox reaction. During the redox reaction, the conversion of these chemical compounds into different chemical or ionic species or intercalation of ionic species into host matrixes either liberates or accepts electrons/ions. The movement of these liberated electrons/ions within the cell creates a current flow out of the battery and powers a device.

All battery devices share a number of similarities in their construction. Each battery cell consists of two electrodes, a positive electrode or a cathode, and a negative electrode or an anode. In between these two electrodes, a layer of separator with an electrolyte exists, which allows the movement of electrons or ions within the cells. Depending on the type of battery, the electrolyte can consist of a liquid, gel or solid material. In addition to these components, batteries also contain additional materials such as insulating separators to prevent the electrodes from physical contact and short circuit, pressure relief valves and other safety features. The combination and integration of multiple battery cells are used to create battery packs with performance characteristics required for the desired application. The choice of chemical compounds determines the nature of the battery device, the redox reaction, cell voltages and energy storage and power capability (Cavanagh, Ward, et al. 2015).

Batteries are classified into two categories: primary and secondary batteries. Primary batteries cannot be recharged, and are more commonly known as disposable or single use batteries. Secondary batteries can be created with certain chemical compounds that can be charged and recharged following use. These charging reactions occur during the course of the battery life cycle. Lithium ion batteries (LIB) are one well known type of rechargeable battery (Cavanagh, Ward, et al. 2015) .

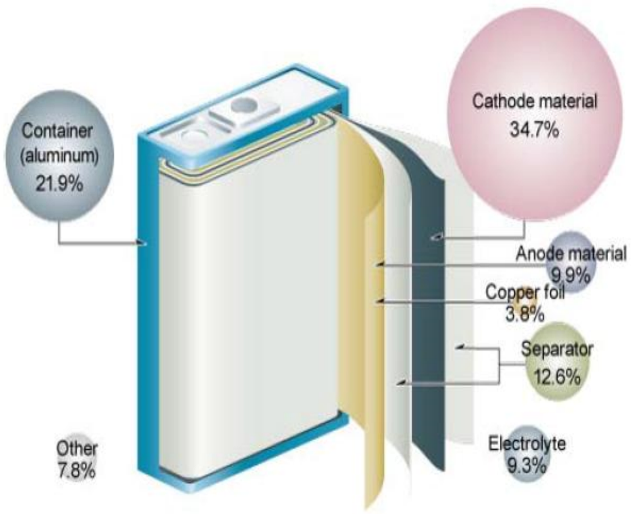

Figure 1: A typical LIB format in the prismatic structure showing the various components.

2.2 Lithium ion battery (LIB) technology

LIB have been commercially available since the 1990s (Gratz et al. 2014; Li et al. 2013). Lithium cobalt oxide ($LiCoO_2$) is traditionally the most commonly used electrode type in mobile phone (Figure 1) and laptop LIB (Li et al. 2013). LIB are typically described based on their cathode materials and these materials account for 90 %

of the material value and around 25 % of the total weight of a battery (Gratz et al. 2014). Table 1 provides an overview of common battery types, uses and LIB global market share, estimated as at 2014 (Gratz et al 2014).

Table 1: Lithium battery types (Gratz et al. 2014; AAS 2017; Lewis 2016)

Type	Application	Estimated global market share (%)
Primary lithium	Single use lithium batteries for consumer electronics. Sizes range from button cells to car batteries.	n/a
Lithium cobalt oxide (LCO) ($LiCoO_2$)	Mobile phones, laptops, tablets, cameras. High energy density therefore useful in portable electronics.	37.2
Lithium nickel manganese cobalt oxide (NMC) ($LiNiMnCoO_2$)	Power tools, electric vehicles EV, energy storage and medical devices. Sometimes combined with lithium manganese in EV to give high energy burst, where NMC provides long range driving.	29
Lithium manganese oxide (LMO) ($LiMn_2O_4$)	Power tools, EV and medical devices. Good thermal stability, high discharge/recharge although a shorter life compared with others.	21.4
Lithium nickel oxide (LNO) ($LiNiO_2$)	EV. Not as thermally stable as other cathodes.	7.2
Lithium iron phosphate (LFP) ($LiFePO_4$)	Energy Storage, EV, medical devices.	5.2

2.3 Lithium battery development

Demand for increased battery performance is growing, especially with applications such as transportation and electricity grid storage and support. This demand is beginning to push existing battery technology to its limits. Next generation materials are being developed principally to reduce the cost of battery production, improve safety and functionality, whilst also improving (or not compromising) performance. Most recycling technologies depend upon recovery of cobalt in order to be profitable (Heelan et al. 2016), but new battery technologies focus on reducing the use of cobalt and nickel in order to reduce production costs (Gratz et al. 2014). This has obvious implications for the value of recycling next generation lithium-based batteries in the future.

Some of the promising next generation candidates include cathode materials such as lithium manganese-spinel (Wang et al. 2014). In addition, graphene has been identified as a good candidate for improving the performance of graphite electrodes (Douthwaite 2015; Brownson et al. 2011). In principle, lithium metal can offer up to 3,860 mA/g capacity compared to the ~360 mAh/g from the current graphite electrodes, due to a concomitant and significant reduction in weight and volume when compared to LIB technology (Figure 2). This order of magnitude increase in energy density and concomitant reduction in battery volume and weight means that potentially Li-metal batteries could potentially approach the same energy density as gasoline for transportation applications (Figure 3) (Bhatt & McCloskey 2010).

The rechargeable lithium metal battery is the next frontier in LIB development and global drivers for an increase in battery energy storage capability is driving current research and development efforts for lithium metal-based rechargeable battery technology (Brotchie 2016). These lithium metal batteries include next generation technologies such as lithium sulfur (Li-S – predicted 2 to 5-fold energy storage capacity increase) and lithium air (Li-air – predicted 10-fold capacity increase), which both will utilise lithium metal anodes.

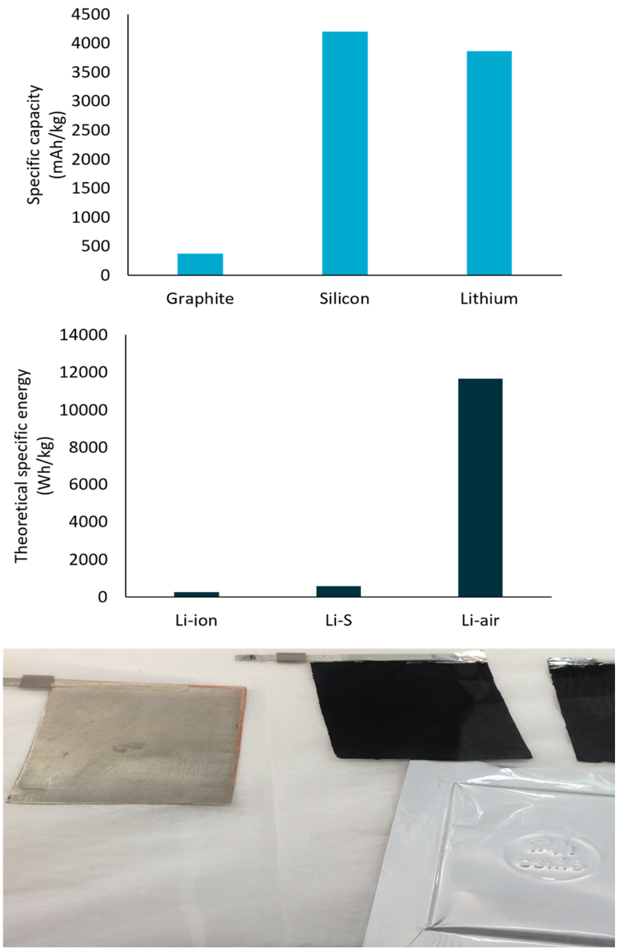

Figure 2: Lithium metal anode capacity and energy compared to alternative electrodes (top) and prototype rechargeable lithium metal battery construction (bottom).

Despite their significant improvements for energy storage capacity, there are significant issues surrounding the commercial application of lithium metal batteries. The formation of dendrites (metal spikes/needles) during the recharge process which can cause short circuiting, poor performance and serious fire safety issues and is a significant issue to be overcome during research and development for these technologies (Matherson 2016).

An example of research and development investment is the Centre CIC Energigune and Hydro-Québec collaborated in 2015 to produce a “safe, powerful and inexpensive” laboratory-scale lithium metal battery with a solid electrolyte (Hydro-Quebec 2015). Another near-to-market example of a next generation battery is manufactured by MIT spin-off company, SolidEnergy Systems. This new next generation lithium battery is likely to be half the size of an existing Apple iPhone battery. This technology uses an ultra-thin lithium metal foil in place of a traditional coated anode and a modified electrolyte to allow the battery to be rechargeable. One of the key benefits of the technology is that is uses existing LIB manufacturing infrastructure for the development of materials. (Matherson 2016). As at 2018, SolidEnergy have a product commercially available for the drone market (SolidEnergy 2018)

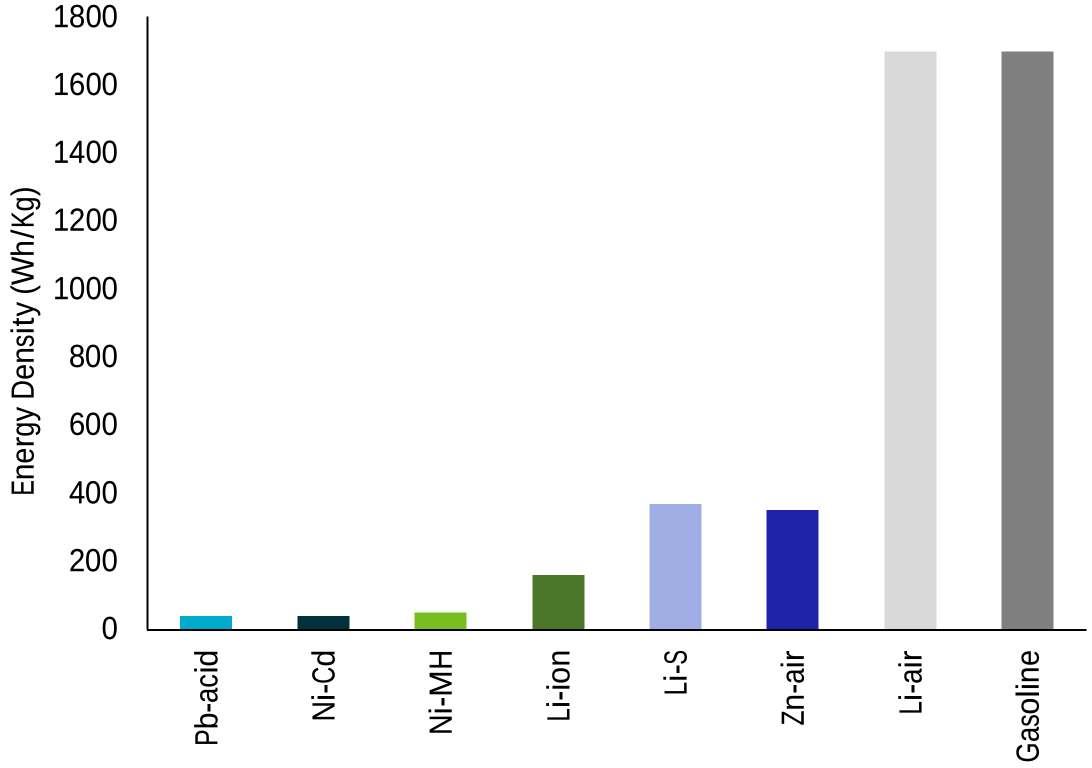

Figure 3: Practically achievable energy density (by weight) of various battery technologies and comparison to gasoline.

3 Resource and material demand for LIB

3.1 Composition and the value proposition

Whether end-of-life LIB are landfilled or exported, the value associated with valuable metals used in the manufacture of LIB is lost from the Australian economy. The potential value of this secondary metal-rich resource, based on the general composition of LIB and commodity prices (as at 19/3/2018) is shown in Table 2. The data shows that the potential value from the recovery of these metals from general LIB with lithium and cobalt contained in the cathode materials (reviewed by Zeng et al., 2014) could be between $AUD 4,400 and $AUD 17,200, depending on the primary metal constituents of the batteries being processed. The data also shows that though cobalt is only present in small percentages, it is still the most important metal for providing an economic driver for the development of recycling processes for LIB waste in Australia. Similarly, nickel, and copper also contribute to the overall economic argument for the recovery of these resources. However, though there is enormous potential to recover value from waste LIB instead of losing them to landfill or overseas, the costs associated with collection, transport, sorting, dismantling and the changing chemistries of these batteries should always be considered when designing processing technology for battery recycling.

Table 2 Potential recoverable value from spent LIB determined by current commodity prices and percent composition of typical LIB with lithium and cobalt contained in the cathode materials. The potential recoverable metal value was determined for both the low and high percent compositions reported in the literature.

Component	Composition[a] (%)	Commodity Value ($AUD/T)[b]	Potential Recoverable Value (2017)	
			Min $AUD/T	Max $AUD/T
Al	4-24	2690.44	63.66	381.97
Co	5-20	115,070.25	3,403.85	13,615.38
Cu	5-10	9,002.39	266.27	532.54
Fe	5-25	75.23	2.23	11.15
Li	1-7	21,453.78	126.92	888.46
Mn	10-15	2,768,47	158.46	237.69
Ni	5-15	17,865.14	528.46	1,585.38
Total			**4,459.85**	**17,252.58**

a (Zeng et al. 2014); b London Metal Exchange and Metalary and AUD to USD conversion by XE.com; accessed 19/3/2018.

3.2 Lithium demand, supply and security

As the demand for portable and rechargeable electronic equipment grows, there is a simultaneous and increasing demand for the supply of lithium to design and develop technical battery materials. Though it is a highly versatile metal that has applications in a broad range of industries including technology, aviation, pharmaceuticals, ceramics and glass and energy, it was estimated that the largest demand for lithium in 2016 was for the manufacture of batteries (35 %) (Swain 2017).

Dakota Minerals estimated that the global demand for lithium (expressed as lithium carbonate equivalent, LCE) was approximately 160 kilo tonnes (kt) per annum in 2015, and was projected to increase to 500 kt per annum by 2025 with an annual compound growth rate between 6 to 10 % pa (Table 3). The largest increase in demand would come from the use of speciality and technical lithium compounds for use in batteries and energy storage, with an estimated growth of 10-15 % or 200-250 kt per annum of lithium required for the manufacturer of these products (Dakota Minerals 2017). It was also reported that future demand for lithium specifically for the use in LIB could increase to as high as 66 % by 2025 (from 35 % in 2015) (Swain 2017).

Table 3: Demand for lithium based on market share to 2025 (modified from Dakota Minerals, 2017).

Application	Lithium products	Current demand (kt per annum LCE)	Growth per annum between 2015-2025
Batteries	Speciality compounds, primarily derived from LiOH	60-70	10-15 % (200-250 kt)
Glass and ceramics	Spodumene concentrates (Li_2O) Li_2CO_3	40-50	2-4 % (55-65 kt)
Greases and lubricants	LiOH	15-20	4-8 % (30-40 kt)
Metal alloys	Li metal and alloys	10-15	3-5 % (15-25 kt)
Air conditioning	Various	5-10	3-5 % (10-15 kt)
Polymers	Various	4-8	2-4 % (10-15 kt)
Medicine	Speciality organo-compounds	4-8	2-4 % (10-15 kt)
Others	Various	10-15	3-6 % (15-25 kt)
Total		**150-170**	**6-10 % (350-450 kt)**

Lithium occurs naturally primarily in continental brines (59 %), and as a hard rock mineral deposit known as spodumene or pegmatite (25 %), with minor amounts forming in other sources such as seawater, hectorite, geothermal brines, oil field brines and jaderite (Swain 2017; Vikström et al. 2013; Mohr et al. 2012).

Australia's lithium resources are exclusively hard rock mineral deposits primarily located in Western Australia, including Greenbushes (hard rock spodumene, 1.9 % Li, 0.3-0.7 Mt), Mt Marion (spodumene with pegmatite sheets, 0.65 % Li, 0.02 Mt), and Mt Cattlin (spodumene, 0.5 % Li and 150 ppm Ta_2O_5, 0.07 Mt) (Vikström et al. 2013). In 2016, it was reported that Australia had the highest production and export of lithium, supplying 40 % of the total lithium across the globe (Swain 2017). It was also identified that the distribution of lithium wealth (i.e. the countries that had the greatest economic position in terms of lithium production) was limited to four countries, namely Chile (52 %), China (22 %), Argentina (14 %) and Australia (10 %).

Western Australia is the lithium mining centre for Australia, and interest in lithium is growing from the mining sector and international investors. With growth in demand for electronic products,

"*Prime Minister Malcolm Turnbull identified lithium as Australia's next major mineral export to China as the super-charged sector continues to ride the wave of an investment boom*" (Lucas 2017).

Strategically, there are connections between the reuse and recycling of LIB and Australia's lithium mining investments. There is also the potential to supplement primary mineral resources with recovered secondary lithium materials of the same grade.

Projections for the life of global lithium resources are variable depending on the factors driving lithium consumption used to model data. The U.S. Geological Survey (USGS) estimated that there was 365 years of static reserve life for lithium commodities in 2015 (U.S. Geological Survey 2015). However, this number is a general index derived from the annual production from reported reserves at a given time and does not take into consideration dynamic factors such as changes to market demand, challenges to production or the impact of recycling and reuse of recovered metals (Humphreys 2014).

Given the drive in lithium demand as a result of increasing uptake of energy storage and EVs, an assessment of accessible lithium resources and whether they were sufficient to meet the growing demand due to roll out of EV was undertaken (Mohr et al. 2012). Using data regarding ultimately recoverable resources (URR), it was shown that the global resource of lithium was between 19 Mt (low) and 55 Mt (high), with the best estimate of 24 Mt of available lithium resources in the world. The study showed that projected lithium supply was sufficient to meet the demand for a 77 % maximum penetration of EV into the market until between 2080 (low) and 2200 (high). It was estimated that the global lithium demand would peak at 860 kt lithium/year, assuming a 100 % penetration of EVs, a population density of 10 billion people, and with 3.5 people per car.

Studies and forecasts suggest that in a 'best-case' scenario, lithium supply from accessible sources will match demand by 2025. In the 'worst-case' scenario, global lithium stocks are conservatively depleted by 2025. This estimate accounts for rising demand of consumer electronics and car production (Wanger 2011). This does not refer to reaching zero lithium, rather lithium prices will steadily rise due to demand, which makes previously uneconomic mining zones feasible and hence recycling more attractive.

Since 2002, there has been approximately a 5-fold increase in lithium metal commodity prices, from $ 1,590/t in 2002 to $ 9,100/t in 2016 as shown in Figure 4(Metalary 2017). This increase in commodity price is primarily driven by the demand for the resource in manufacture of LIB, and resource constraints such as limited supply and resources being dominated by only a few countries. Projections about lithium demand in the future in response to roll out of EV and larger grid or off-grid energy storage devices will ensure that the commodity prices continue to increase and primary resources will continue to be depleted, and this will therefore contribute to the drive to recycling lithium containing consumer products, such as LIB.

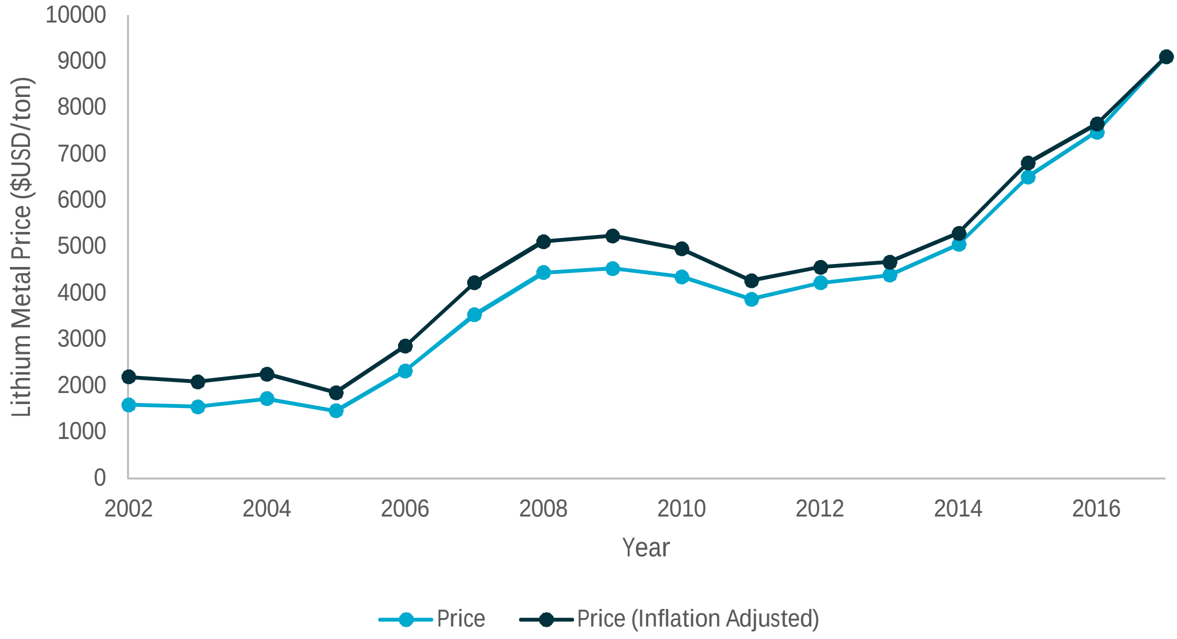

Figure 4: The increase in lithium metal prices ($USD/ton) from 2002 to 2016, inclusive (values derived from Metalary, 2017).

Currently, less than 1 % of lithium used in consumer products is recycled from various sources (Swain 2017). Similarly, less than 3 % of all LIB produced globally are recycled, and from recycled LIB, the recovery of lithium is considered to be negligible (Vikström et al. 2013; Wang et al. 2014). This highlights the global gap in technology to capture the lithium from end-of-life LIB. Though Australia holds a significant share of primary lithium mineral reserves, the country is lacking technology and infrastructure for the manufacture of technical grade lithium products, such as batteries. The Australian Mining Executive Council (AMEC) recently identified that there is a significant opportunity for Australia to become a market leader in the manufacture of these products (Wills et al. 2018). In addition to supporting traditional mining and export of raw materials, this would add to the Australia's lithium value supply chain, and also provide an onshore end-user for secondary lithium products recovered as a result of LIB recycling.

3.3 Cobalt, a critical metal

Cobalt is utilised in the cathode of LIB such as LCO or the more recent NMC and NCA chemistry variants. Cobalt is classed as a critical metal and as such the commodity price is high, currently at $ AUD 115,070 per tonne (Table 2) (European Commission 2017). Since a key economic driver for LIB recycling is the recovery value of cobalt, it is worth mentioning the criticality and social licence to operate issues associated with the mining of the metal. Both lithium and cobalt have been ranked by Geosciences Australia as critical, and subsequently categorised as category one and two, respectively, in terms of strategic resource potential and opportunity for Australia to supply resources to meet the global demand for technology (Skirrow et al. 2013). The high criticality of cobalt is linked to the fact that 50 % of world production is from the Democratic Republic of Congo. Other key commodities mined in this region are gold and coltan (a tantalum ore). There are concerns over the armed conflict, illegal mining, human rights abuses and environmental issues from this poor region of the world. This has prompted the information, communications & technology industry to form the Conflict-Free Smelter Initiative, and the Australian Mobile Telecommunications Association (AMTA) are part of this initiative (AMTA 2014).

3.4 Other secondary commodities

In addition to the high economic drivers of lithium and cobalt, the manufacturers of LIB also consume other primary materials that have the potential to be recovered and used as secondary materials in either new products or new LIB. These include base and other metals (copper, zinc, nickel, iron and aluminium), plastics, electrolyte materials and technical materials such as graphite. Market reports indicate that the demand for graphite to manufacture new LIB will likely treble over the next 4 to 5 years in line with the demand for portable and rechargeable equipment (Benchmark Mineral Intelligence 2016). As the graphite is a relatively inert material, it is possible to recover and reuse it as technical grade graphite for new batteries or to convert it into better technical grade materials, such as graphene. Though these materials are not currently the primary economic drivers for developing recycling processes for LIB, they are still materials that should be considered when defining the value proposition of an onshore LIB recycling process.

4 Production and use of LIB

4.1 Global production of LIB

The improved energy density over nickel metal hydride batteries makes LIB applicable to consumer electronics including mobile phones and laptops, as well as for energy storage and EV, hybrid electric vehicles (HEV), and plug-in hybrid vehicles (PHEV) (Zeng et al. 2014; Li et al. 2013). The expected life of batteries varies between 3 years for consumer products and 10 years for EV (Wang et al. 2014). The importance of research into reuse and end-of-life is growing in importance as global production of LIB is predicted to increase 520 % over 2016 to 2020. Much of this increase in capacity driven by Chinese manufacturers as shown in Figure 5 (Desjardins 2017). Australia does not currently manufacture LIB although there have been media reports of a proposed LIB factory for Darwin (Daly 2017).

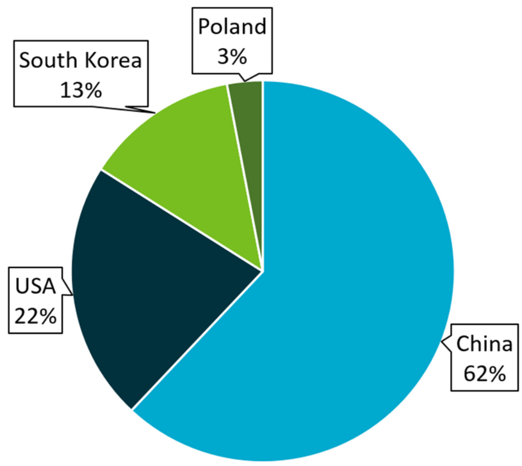

Figure 5: Global production of LIB, image reproduced from data in (modified from Desjardins 2017).

4.2 How Australians use LIB

4.2.1 Mobile phones

Mobile phones are a common consumer electronic device. The total number of phones in use and in storage in Australia has stabilised at 46 million, or 2 phones per person. Sales of mobile phones ranged between 10-13 million per annum between 2008 and 2014. It is perhaps not surprising to know that many mobile phones are kept in storage and this accounts for approximately 50 % of in-use stock (Golev et al. 2016). While the lifespan of a mobile phone is theoretically 10 years, consumers generally update their phone more frequently than the maximum operating life. In Australia, the average lifespan of a phone is between 3.5 – 4.5 years, with an estimate of 3.8 years for the period 2010-2014 (Golev et al. 2016).

Modern mobile phones consist of approximately 25 % metal, 30-50 % plastic and the remainder comprises glass, ceramics and epoxy. Mobile phone recycling currently only recovers the metals including copper, silver, gold and platinum group metals. One estimate of the recycling efficiency of the metal fraction was between 48-64 %, which only equates to 12-19 % of the total mobile phone being recovered (Geyer & Blass 2010). Mobile phones can also include materials with varying levels of toxicity, such as cadmium, beryllium, mercury, hexavalent chromium, bromated and chlorinated flame retardants and gallium arsenide. The components of a mobile phone do not pose a threat during their use. However, the disposal and treatment of a mobile phone at the end-of-life must be considered to ensure that toxic materials do not pose a threat to human and environmental health.

4.2.2 Handheld batteries and consumer electronics

Handheld batteries are defined as those that are less than 5 kg in weight, and include primary (single-use) or secondary (rechargeable) batteries. Handheld batteries include applications such as mobile phones, laptops and power tools. The average life of the majority of primary batteries is estimated to be 1.8 years. Total Australian sales of handheld batteries for all chemistry types for 2012-13 totalled 17,500 tonnes. The sales of secondary lithium chemistry batteries accounted for 24 % of all batteries by weight, and strong continued growth is expected (O'Farrell et al. 2014). More specifically, there were sales of 120 tonnes of primary handheld lithium batteries and 4,130 tonnes of LIB during 2012-13 in Australia. Australian in-use stocks of secondary LIB is growing significantly, from just over 11,000 in 2012-13 to a forecast of almost 30,000 by 2019-20 (O'Farrell et al. 2014).

4.2.3 Australia's electric vehicle market is developing

Globally, the EV market reached over 1 million cars on the road in 2015 (International Energy Agency 2016). Based on 2015 data, China is the biggest global market for EVs, including electric scooters and buses. EV adoption is boosted in countries with supportive policies and targets and of all countries, Norway has the greatest market share of 23 % (International Energy Agency 2016).

Since 2008, there has been a performance increase in PHEV energy density while at the same time a significant reduction (over 70 %) in manufacturing cost, approximately USD 1000/kWh to USD 268/kWh (International Energy Agency 2016). The reduction in cost makes EV and PHEV more competitive with internal combustion engines, and greater energy density allows for longer distances to be travelled on a single charge. Some EV manufacturers have set ambitious goals and commitments to increase passenger vehicle driving range to over 300 km per battery charge (International Energy Agency 2016).

Current Australian EV sales are weak, and account for 0.15 % of new car sales in Australia. There are an estimated 4,500 EV on Australian roads as of June 2016 (Asghar 2016), and only 1,100 were sold in 2015 (Lewis 2016). The majority (47 %) were the Mitsubishi SUV PHEV, with the Tesla and Nissan Leaf both contributing 15 % of the EV sold in 2015 (Asghar 2016). Current consumer purchasing incentives vary by state and are not significant enough to encourage the adoption of EVs, which means that Australia remains an 'early adopter' for their purchase. States and Territories have different approaches to increasing EV adoption. For example, the Queensland Electric Superhighway project has installed fast charging stations between Cairns and Toowoomba (Queensland Government 2017). The aim is to encourage, support and accelerate the uptake of electric vehicles in Queensland where stations are initially free to use. The infrastructure will enable travel from Gold Coast to Cairns and from Brisbane to Toowoomba in a low or zero emissions vehicle. Through schemes such as this, it is anticipated that the EV sales in Australia will grow and the forecast EV sales in Australia are moderate with total sales expected to increase to 425,000 by 2030 (Figure 6) (Asghar 2016).

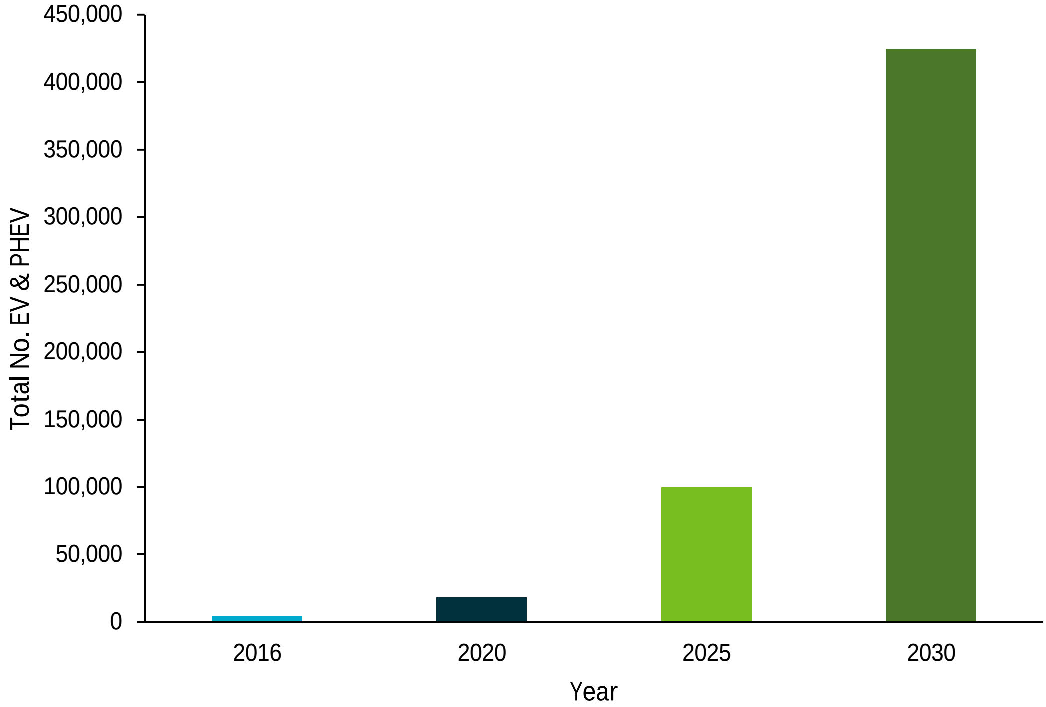

Figure 6: Current and forecast of electric vehicle (EV) and plug-in hybrid vehicles sales in Australia (Asghar 2016).

4.2.4 Batteries for energy storage, another emerging market in Australia

The use of large energy storage batteries is rapidly emerging in Australia, most widely highlighted by the South Australian 100 MW installation in 2017. This is currently the largest energy storage installation of its kind in the world. The lifecycle impacts of energy storage batteries were detailed in a report that reviewed NMC and LCO based chemistries for lithium energy storage batteries (Florin & Dominish 2017). While several other battery chemistries were reviewed, these two chemistries were rated as the most significant in terms of likelihood of deployment and adoption for residential and commercial applications. The report identified a need to develop a sustainable supply chain for metals and to engage industry to adhere to best-practice initiatives for the use of energy storage batteries (Florin & Dominish 2017). The report also highlighted the need for end-of-life waste battery management, even in this emerging product area.

5 LIB waste generation: data, predictions, fate and value

5.1 Summary of LIB waste generation data

Australian LIB waste generation and recycling data is reported in many sources, for different years, products and chemistry types. Australia has a very poor collection rate for batteries, with only 1.8 % (2012-13) of lithium batteries being recovered, and the remainder disposed to landfill (O'Farrell et al. 2014). A summary of key LIB waste generation data and forecasts for Australia is provided in Table 4.

Table 4: Summary of LIB waste generation data and forecasts for Australia, reported by product or as total LIB wastes.

Type	Units/Tonnes	Data Year	Reference
Mobile phones (storage)	22.3 million units	2014	(Golev et al. 2016)
Mobile phones (end-of-life)	12 million units	2014	(Golev et al. 2016)
Total LIB waste	3,340 tonnes/year	2016	(Randell 2016)
Total LIB forecast	137,618 tonnes/year	2036 ("best" most likely forecast)	(Randell 2016)
Handheld lithium primary – waste to landfill	140 tonnes/year	2012-13	(O'Farrell et al. 2014)
Handheld LIB – waste to landfill	1,720 tonnes	2012-13	(O'Farrell et al. 2014)

Estimating counts or tonnage of available LIB is inherently difficult. Many authors attempt this task using different methodologies. In 2010, a stocks and flows study was published to account for lithium battery consumption, recycling and disposal in Australia (Warnken Industrial and Social Ecology Pty Ltd 2010). Key findings from this 2010 report include:

- Lithium battery handheld inputs per year were 1,960 tonnes and 12 % of the chemistry type (by weight). By comparison, large and industrial batteries were 1,500 tonnes per year accounting for 3 % (by weight) of total battery chemistries;

- Of the handheld batteries, 8,000 tonnes were being landfilled, some of which would be LIB. Only 4 % of all handheld batteries were being recovered; and,
- On a count basis, 70 % of all batteries were being sent to landfill and the majority of this waste was from handheld batteries.

The variability and difficulty in collecting data illustrates the difficulties in understanding stocks and flows for LIB from sales to end-of-life in Australia, and poses challenges for forecasting and predicting future trends. The combination of increasing demand for LIB is rapidly growing, and poor collection and recovery of materials in Australia means that there is considerable scope for improvement in data collection and materials tracking directly related to LIB waste generation and fate. Given the large increases forecast to occur with this waste stream it is important we continue to monitor in use stocks and end of life data.

5.2 Future LIB waste predictions are clear: we have a problem

More recently, it was forecasted that LIB waste is growing at a rate of 12 % each year in Australia and given the associated fire and/or explosion risk with LIB, there is a need to assess collection and processing infrastructure for end-of-life LIB (Randell et al. 2015). However, more recent data gathered by the same author indicated that the 2015 forecast was underestimated due to a lack of pertinent data, and an annual growth rate of 19-22 % was more realistic for LIB waste (Randell 2016).

LIB waste generation forecasting in 2016 predicted that 3,300 tonnes in 2016 to 137,000 tonnes by 2036 (medium growth projections) as a result of per capita consumption of handheld and rechargeable equipment, the introduction of EV and the concurrent production of waste EV batteries, and increasing use of solar and photovoltaic panels (Randell 2016). The best-case scenario as well as sensitivity analysis for high and low projections are shown in Figure 7.

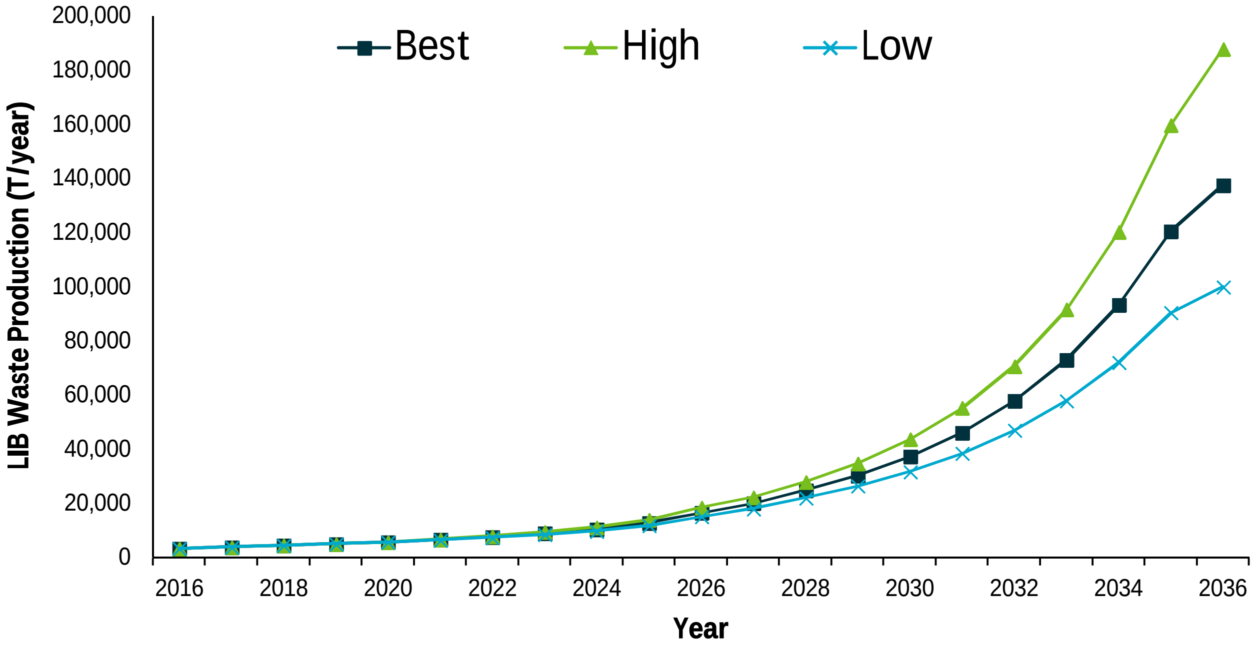

Figure 7 Projected LIB waste production from 2016 to 2036 (modified from Randell et al., 2016).

Based on the general composition of these batteries (see Table 2), the current value of metal commodities, and scenario projections for battery waste production, it was calculated that one tonne of battery waste has potential recoverable value of between $AUD 4,550 and $AUD 17,252 (as at 19/3/2018), with the majority of value as a result of the presence of cobalt (Table 5). These values do not include other materials such as graphite, plastics or electrolyte materials or take into consideration other costs association with collection, transport or processing of battery wastes.

Table 5 Potential recoverable metal value from current and projected future spent LIB based on commodity prices from 19/3/2018.

	2016	2036
Waste Production (T)	3,340[a]	137,618[a]
Potential recoverable metal value for 1 T of waste ($AUD)[b]	Min 4,550 Max 17,253	
Potential total recoverable metal value ($AUD)	Min $ 19.7 million Max $ 74.9 million	Min $ 813 million Max $ 3.09 billion

[a] current and projected volumes of spent LIB as described by Randell et al., 2016; [b] as calculated from commodity prices and exchange rates as described in Table 2.

A report reviewing Australia's capacity to manage and treat our hazardous wastes concluded that Australia's overall e-waste capacity was adequate until 2034, with the exception of Western Australia and the Northern Territory, where no e-waste recycling infrastructure currently exists. Moreover, it was noted that Australia has no specific LIB collection, transfer or treatment infrastructure, and instead relies on the collection and separation of mixed battery types, disposal to landfill, or exporting for recycling (Randell et al. 2015). The report recommended that the hazards associated with handling, management, disposal and transport of LIB in Australia be assessed, along with the collection techniques and processing infrastructure for Australia to meet future waste treatment and resource recovery targets (Randell et al. 2015). The following year, a report into LIB waste concluded:

> ***"there is an immediate need to improve processing infrastructure capacity for handheld Li-ion batteries in Australia"*** (Randell 2016, p.12)

The combination of the lack of technology to deal with this growing and complex waste stream, and the inherent value that is currently being lost to landfill or international economies, as well as spent batteries being identified as a priority area for Australian waste management (Australian Government 2018) means that there is significant potential for targeted research to develop strategies and technologies for the recycling and processing of spent battery waste in Australia.

Part II
Australian lithium battery recycling

Current practices and an international perspective

6 E-waste and battery recycling is developing in Australia

From collection to processing, the recycling of lead and nickel/cadmium batteries is a well-established and well-regulated process in Australia. However, there are no comparable processes or practices in Australia for the recovery of value from for LIB, despite being shown to be economically feasible. Consumer awareness of recycling options is the major limitation for recycling as available end-of-life stocks are not being captured or collected, and this prevents recycling systems from operating efficiently. Certainly for mobile phones, it is social rather than economic or technical issues that reduce the effectiveness of recycling (Sarath et al. 2015).

A number of programs designed to promote the recycling and reuse of waste LIB have been developed and are discussed here. Though collection is occurring, the recovery of value from these waste still largely depends on export to other countries to complete the recycling value chain, and a significant amount of collected batteries are still disposed in landfill.

6.1 Mobile phone recycling

It was estimated that 12 million end-of-life mobile phones existed in Australia in 2014, with an additional 22.3 million mobile phones kept in storage (Golev et al. 2016). Many of these contained a LIB but were not in active use (Golev et al. 2016).

Mobile phones can be recycled through a number of private e-waste providers. However, the most well-known recycling scheme in Australia is MobileMuster (Figure 8). This is a not-for-profit scheme funded by the AMTA, which works with many (but not all) mobile phone manufacturers and distributers to promote the recycling and reuse of end-of-life mobile phones. Some manufacturers such as Apple have their own recycling scheme. MobileMuster operates to educate, raise awareness and collect mobile phones across Australia.

In 2015-16, MobileMuster reportedly collected 76 tonnes of mobile phones which included 16,500 kg of batteries, most of which would be LIB (AMTA 2016). MobileMuster has proven very effective for capturing end-of-life mobile phones, diverting them from landfill, and serves as a model for future voluntary product stewardship schemes in Australia.

Figure 8 Mobile Muster Recycling Process (MobileMuster 2013).

6.2 Handheld battery recycling

Handheld batteries include batteries contained within mobile phones, laptops, power tools and most handheld electronic devices. Based on data from O'Farrell et al (2014), the number of handheld batteries reaching end-of-life for 2012-13 was forecasted to be:

- 150 tonnes primary lithium batteries; and,
- 1,750 tonnes of LIB.

The recovery rates for the same period were:

- 7 tonnes or 4.8 % of primary lithium batteries; and,
- 31 tonnes or 1.8 % of LIB.

This means that a total of 1,860 tonnes of primary lithium batteries and LIB were landfilled or informally stockpiled for the 2012-13 period, which indicates that battery collection and recycling is a significant issue for Australia.

6.3 Electric vehicle and energy storage battery recycling

The LIB chemistries used for EV applications are similar/same as those used in energy storage systems. Further, the construction of these systems also has numerous similarities for both applications, albeit with differing sizes and electrical performances. From a recycling perspective, the initial applications, i.e. storage or transportation, does not change the end-of-life processing significantly.

6.3.1 EV battery recycling

The Federal Chamber of Automotive Industries (FCAI) is the peak body representing manufacturers and importers of vehicles in Australia. FCAI state that all of their members have a system in place to take back batteries at the end-of-their life. For a recent report by Helen Lewis (2016), interviews were held with major car manufacturers regarding their end-of-life options for batteries from their EVs. It was found that some companies provide incentives to collect and swap batteries once end-of-life is reached. This included Toyota, which has a rebate or discount on new batteries when old batteries are returned to manufacturer (Lewis 2016). Another large global car manufacturer stated that once required in Australia, they would make arrangements with local recyclers to take on end-of-life batteries and recycle them, ensuring that they conform to strict standards (Lewis 2016). Another global car manufacturer has a closed loop recycling process where batteries are returned to the original equipment manufacturer (OEM). However, many EV batteries have yet to reach end-of-life in Australia and therefore this market is presently undeveloped.

The EV battery components are typically stored within modules and there are many modules distributed across the vehicle. For example, to demonstrate the configuration of EV batteries, the Nissan Leaf battery configuration has 48 modules, each the size of a laptop. The battery chemistry in use is blended cathode material (LMO with LNO). Within each module is an individual pouch

(Figure 9). This equates to approximately 250 kg of batteries in each Nissan Leaf. End-of-life is expected to be approximately 10 years when batteries could be expected to have 70 to 80 % of their original capacity. At this capacity, this will reduce the EV range, and hence will require replacement (QNovo 2017).

While currently, almost all EV batteries are exported from Australia for end-of-life processing, it is unlikely that these batteries will be immediately processed for recycling in future. Most car manufacturers advertise that they are exploring new energy storage markets for spent EV batteries, otherwise known as "second life", given their capacity levels will still be greater than 50 % (Lewis 2016).

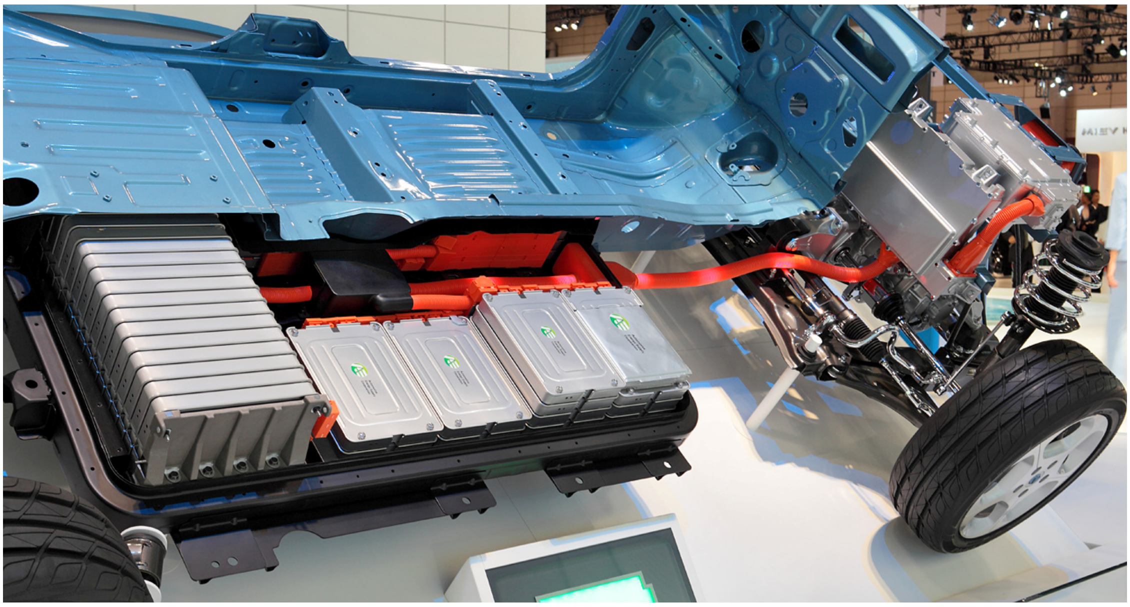

Figure 9: Nissan Leaf battery modules (www.wikipedia.com).

6.3.2 Recommendations for improved EV recycling

A comprehensive study (Gaines 2014) on future considerations for automotive LIB recycling discussed the lessons learned from other earlier battery types, such as the lead acid battery. The study noted that lead acid battery recycling was effective because the batteries were of a standard design and disassembly protocols, there was only a single chemistry type that did not require segregation (unlike LIB), and as such, the recycling process was simple. In addition, lead acid battery recycling was also driven by Federal and State Government regulation making it illegal to dispose them to landfill. These factors ultimately allowed the development a profitable recycling industry for these batteries.

When compared to LIB, lead acid batteries have a standard location in the vehicle. LIB can be distributed across the vehicle and are more complex to remove. LIB in EV are complex, with 100-5,000 individual cells, comprised as modules within a pack, connected to a circuit panel (Figure 10). As such, removal and discharge process is also complicated, requiring trained professionals and a high level of manual handling to correctly disassemble the battery from the car (Gaines 2014).

Given the challenges associated with the design and assembly of LIB, the study by Gaines (2014) recommended that recycling of these batteries could be promoted and made more efficient and economically viable through the use of economic incentives, regulation to enforce recycling and resource recovery, effective and standardised labelling for efficient sorting and segregation, improved separation technologies for variable cathode materials, and an overall standardised design of LIB batteries for EV use (Gaines, 2014).

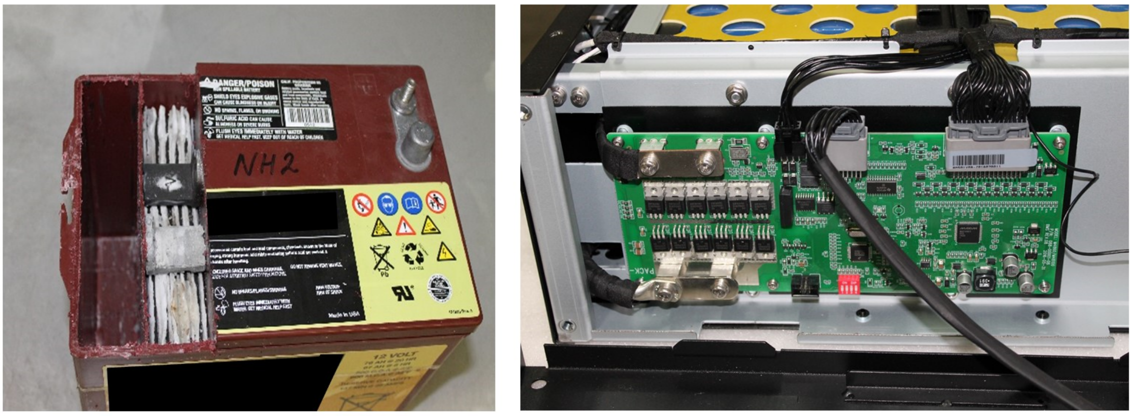

Figure 10: Lead acid battery (left) and LIB (right).

6.3.3 Energy storage battery recycling

Energy storage batteries cover a range of applications including grid-connected systems (e.g. residential solar storage) and grid support (e.g. frequency regulation, backup power), as well as off-grid or standalone applications (e.g. remote area power, backup power, micro grids). Energy storage battery construction is similar for all applications with the differences mainly lying in size (number of cells) and associated hardware and/or firmware (Figure 11).

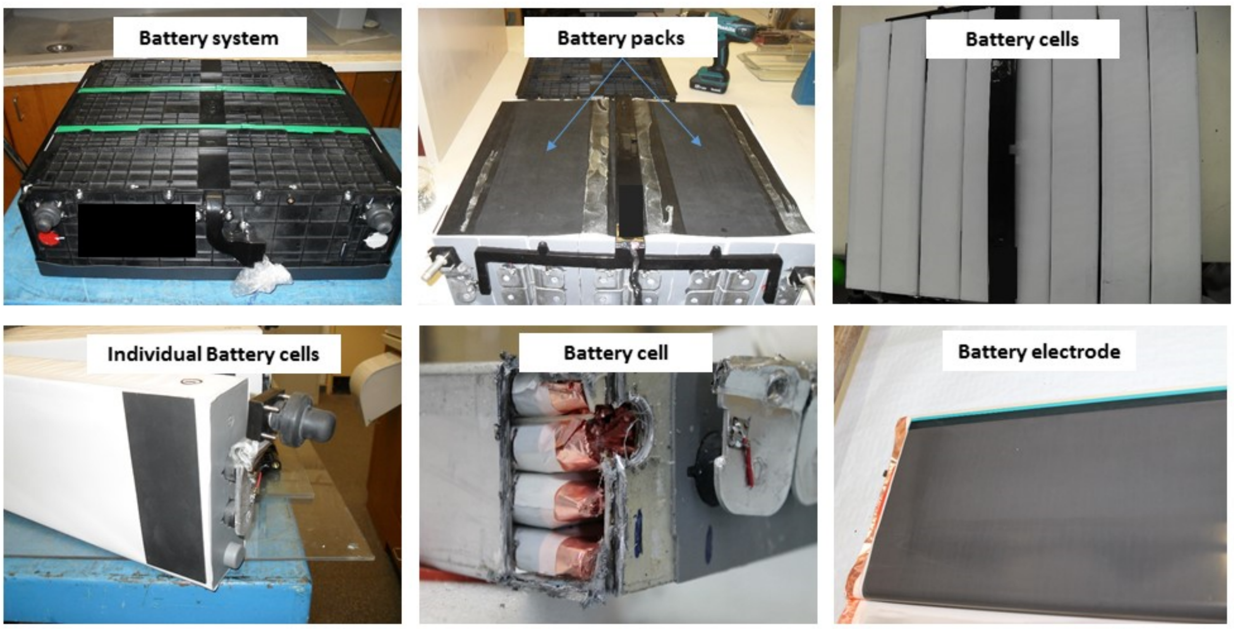

Figure 11 Example of energy storage battery components.

The battery cells are in single modules comprised of either spiral wound cells (most common 18650 format, similar in size to a D-sized alkaline battery) or in pouch and/or laminate cell format. The number of modules is dependent on the overall energy storage unit size and partially determined by the LIB chemistry. In addition to this battery pack, a range of sensors, battery management system and communications electronics also is present. Some manufacturers also place the invertor required for connection to the grid/load inside the system box. Dependent on the overall size of the energy storage system, there may also be additional electronics and hardware in place. Typically the battery packs will contain some form of cooling system, from simple air flow through to complex liquid cooling and associated hardware. These additional hardware components are similar to those found in EV systems.

Although the major LIB cell manufacturers are the same as EV cell manufacturers, there are numerous pack and system assemblers and retail organisations. This means that the supply chain within the electricity grid and off-grid battery sector is more complex than the automotive sector. The retail sector is at an early stage within Australia and there is a 10-15 year lead time before batteries need to be recycled. Many companies do not yet have, and are not required to have, a recycling plan in place for end-of-life batteries (Lewis 2016).

6.4 Australian battery recycling is a developing industry

There are only a small number of battery recyclers in Australia. Most collect and export batteries for processing. There are seven companies listed on the ABRI website as providing a collection and recycling service for LIB: CMA Ecocycle; Envirostream; MRI (Aust) Pty Ltd; PF Metals; Powercell (Australia) Trading Pty Ltd; SIMs Recycling Solutions; and Tes-Amm Australia Pty Ltd (ABRI 2018). Of all these companies, Envirostream is the only company in Australia that undertakes a form of initial domestic pre-processing for end-of-life batteries and other e-waste. However, valuable cathodic powders are exported offshore for recovery which means the value is realised by other countries.

Envirostream Australia, a company created by PF Metals, is a family owned and operated company of metal recyclers based in Melbourne, Victoria. In 2015, they announced they would begin processing batteries at the Melbourne site. They accept LIB, NiMH and silver oxide batteries. Any batteries dropped off at their Melbourne site are currently processed free of charge (as of February 2018). Their process consists of sorting by chemistry, and alkaline, lithium, nickel and lead based batteries are processed separately (Lewis 2016). Batteries are discharged, disassembled, granulated and the dust fraction containing valuable metals is recovered. This dust fraction contains aluminium, copper and steel, which are removed and recycled locally. The remaining dust containing lithium, cobalt, manganese and nickel, is exported to Korea for hydrometallurgical processing and recovery of the metals. Plastics are also recovered and sold for reuse. PF Metals stated on their website that they recover 95 % of the battery waste stream (PF Metals 2017).

New recyclers are also developing a footprint in Australia. One example is Neometals in WA who is currently at a pilot scale stage with plans to build a commercial lithium battery recycling plant in 2019. Neometals is a company with lithium mines in Mt Marion and a LiOH production facility in Kalgoorlie, both located in Western Australia. More recently, Neometals has been running a lithium battery recycling pilot-plant in Montreal, Canada and is in the process of commercialising this technology and developing plants in Australia (Neometals 2018).

7 Recycling and reuse of LIB

Though no complete recycling process for LIB currently exists within Australia, the development of technology for resource recovery is being developed on a global scale, and is practiced commercially in a number of European and Asian countries. Similarly, the reuse of LIB to make second-life batteries is also a key research area in Australia and around the world. This chapter reviews literature regarding the technical recovery of value from or reuse of LIB waste.

7.1 Collection, sorting, dismantling

Efficient resource recovery from any waste stream relies on collection and sorting processes at the front end of the process. Generally, the collection, sorting and pre-processing of wastes is the most significant challenge associated with efficient recycling, and relies on the consumer to undertake the majority of the work at the home or workplace to ensure that relatively clean, contaminant-free waste streams can be supplied to recycling facilities. Many studies have reported that consumer behaviour can impact the downstream efficiency of recycling programs, and as a result, consumer education and awareness programs are required to promote resource recovery rates (Park & Ha 2014).

Collection, sorting and dismantling of LIB is also a significant challenge for the recycling and processing of battery wastes. Collection and transport costs for waste management are high in Australia due to freight distances between population centres, without considering the collection of specialised and segregated wastes streams such as LIB wastes. In general, most battery waste is mixed, and although some automated sorting exists, a large amount of manual sorting is still required. This is mostly due to inconsistencies related to chemistry type and the poor labelling of battery wastes. Usually, manual dismantling to remove plastic covers, and shredding and milling are the minimum requirements for LIB processing, but often chemical or thermal pre-treatment is required prior to metal recovery.

The overall value that could be recovered from battery waste would be largely dependent on the cost of collection, transport and dismantling and sorting of the waste prior to processing and the fluctuation of commodity prices over time, and these will significantly change the economic feasibility of process design and development for recycling in Australia.

7.2 Metals recovery

Metals are traditionally recovered from e-waste, including spent batteries, using pyrometallurgical or hydrometallurgical techniques (Zeng & Li 2014; Xu et al. 2008). A summary of some of the major global companies, their processes, product and capacity for LIB recycling is summarised in Table 6 (Heelan et al. 2016).

Table 6 Summary of global lithium battery recyclers (Heelan et al., 2016b).

Company	Process classification	Product	Annual capacity
ARetriev	Hydrometallurgy	Cobalt cake, Li_2CO_3, Cu/Al foil	3,500 tonnes
Umicore	Pyrometallurgy and hydrometallurgy	Co-Ni-Cu alloy, cathode slag for construction materials, Fe	7,000 tonnes
Recupyl	Hydrometallurgy	$Co^{(III)}OH_3$, Li_2CO_3, steel	110 tonnes
Xstrata Nickel	Pyrometallurgy	Ni, Co, Cu alloys	3,000 tonnes
Batrec	Mechanical treatment and hydrometallurgy	Co, Ni scrap, non-ferrous metals, Mn oxides, plastic	1,000 tonnes
Accuree	Pyrometallurgy	Co alloy, Li_2CO_3	1,000 tonnes

7.2.1 Pyrometallurgy

Pyrometallurgy typically involves the direct smelting of wastes at high temperatures and typically has high recovery of valuable metals, such as cobalt and nickel, from battery waste. Processes are robust and do not need to be specifically tailored for the treatment of a waste with specific composition, which is an advantage for heterogeneous wastes like e-wastes and battery waste. However, there are a negative environmental impacts due to high energy consumption and emissions of pollutants (e.g. CO_2, dioxins and furans), and the loss of lower value metals and materials such as lithium, manganese, iron or aluminium and plastics, which are difficult or not feasible to recover (Pagnanelli et al. 2016; Zeng & Li 2014; Xu et al. 2008).

7.2.2 Hydrometallurgy

In principle, hydrometallurgical treatment of battery wastes can allow the recovery of all metal and non-metal components present in the waste. However, a significant amount of pre-treatment is required to promote recovery efficiency. Often, pre-treatment is manual, and when undertaken at large-scale, this manual pre-treatment can result in high processing costs (Pagnanelli et al. 2016; Zeng & Li 2014). This allows the recovery of most plastics associated with the casing materials. The pre-prepared electrode powders are then subject to digestion with acids or alkalis in order to solubilise metals contained in the waste. The cost and regeneration of reagents, as well as treatment of hazardous waste that are produced are also significant issues with hydrometallurgical processing. Metal recovery can also be affected detrimentally by small changes in feed composition. Waste generated from LIB is heterogeneous, often containing variable concentrations of many metals, and hence, processing with hydrometallurgy can be difficult (Pagnanelli et al. 2016; Zeng & Li 2014).

LIB are characterised as polymetallic secondary resources, with predominantly metal oxides and hydroxides as the main metallic components (Xin et al. 2009). Previously, leaching of spent LIB has been undertaken using strong (< 2 M) inorganic acids (HCl, H_2SO_4, HNO_3) at elevated temperatures (< 70 °C) with yields close to 100 % for both lithium and cobalt (Jha et al. 2013; Contestabile et al. 2001; Zhang et al. 1998; Hendrickson et al. 2015; Li et al. 2009). Leaching efficiencies for both lithium and cobalt become reduced when leaching is undertaken at lower temperatures and with weaker inorganic or organic acids, which indicates that the mechanism of leaching is by acid dissolution (Zeng, Li & Liu 2015; Z. Li et al. 2014; Niu et al. 2014; Mishra et al. 2008). The efficiency of cobalt and manganese recovery has been improved by the addition of reductants to solution which promote the conversion of Co^{3+} to Co^{2+} and Mn^{4+} to Mn^{2+} for the recovery by downstream processing, and also reduces the volume and strength of acid required for metal dissolution (Meshram et al. 2015; Zhu et al. 2012; Chen et al. 2011).

7.2.3 Next generation battery recycling processes

Alternative leaching reagents, the regeneration of reagents and the treatment of waste products are the focus of much research directed at reducing the environmental footprint of hydrometallurgical processes in general (Kaksonen et al. 2014a). Ferric iron is commonly used as a lixiviant (liquid medium used for metal extraction in hydrometallurgy) as it can be produced biologically in a low cost and efficient manner, and is effective as a strong oxidant for leaching sulfide minerals and mine wastes (Rawlings et al. 2003; Rawlings 2002; Kaksonen et al. 2014b; Dutrizac & MacDonald 1974).

The chemical production of ferric iron from ferrous iron with oxygen as the oxidant is very slow. The iron oxidation rate can be substantially improved with the addition of iron oxidising microorganisms, especially when the pH of the system is below 2 (Colmer et al. 1950; Colmer & Hinkle 1947; Bosecker 1997; Rawlings 2002). Bioleaching, or the use of microorganisms to assist with mineral and metal leaching processes, focusses on the use of these iron oxidising microorganisms to produce ferric iron lixiviant instead of using inorganic acids, such as hydrochloric, sulfuric and nitric acid, and oxidants, such as hydrogen peroxide, to drive the leaching processes. The ferric iron acts on the mineral and is reduced back to ferrous iron to complete the iron oxidation-reduction cycle. This, in combination with sulfur oxidation undertaken by sulfur oxidising microorganisms to produce biogenic acids results in efficient decomposition and solubilisation of sulfide minerals in ores and waste materials that may be difficult or uneconomic to process traditionally.

Whilst bioleaching remains a viable option for the treatment of most metal containing wastes, previous research has indicated that the microorganisms that are commonly used to assist with metal recovery from minerals and wastes from mining and industry are inhibited by less than 1 % (w/v) pulp density of battery waste due to the polymetallic and complex nature of the waste (Mishra et al. 2008; Zeng et al. 2012; Niu et al. 2014). This means that the traditional application of iron and sulfur oxidising microbes for the direct bioleaching of battery waste may not be suitable. However, the generation of ferric iron by iron oxidising microorganisms and the application of the biogenic ferric iron to battery waste in a separate system still warrants further investigation.

In addition to ferric iron, other alternative lixiviants such as organic and amino acids as well as acids generated by other alternative processes, have been investigated for their use in metal recovery from battery waste, as they are comparatively more environmentally friendly and biodegradable than their inorganic chemical counterparts (Li et al. 2014; Li et al. 2015; Zeng, Li & Shen 2015; Boxall et al. 2018).

In most instances, these lixiviants have been shown to be less stable and less efficient in the leaching due to their lower strength and the reagent consuming nature of the battery waste itself. In most studies undertaken to date, the use of these biologically produced reagents results in less efficient solubilisation of metals, but there is potential to improve leach yields by optimising battery waste pre-treatment and leach conditions.

7.3 Recovery of other materials

In addition to the recovery of metals, there is further opportunity to recover and recycle other materials used in LIB manufacture to further add value to processing of these wastes (Moradi and Botte, 2016; Singh et al., 2017; Sabisch et al., 2018). Recycling and reuse of plastics associated with battery casings without using pyrolysis would also reduce the environmental impacts associated with processing (Boyden et al., 2016). Generally, plastics can be recovered at the mechanical processing stage, where plastics, copper, aluminium and steel can be selectively removed during crushing and sieving (Xu et al. 2008). This pre-processing of the LIB waste allows concentration of the valuable cathodic components prior to recovery via pyrometallurgy, hydrometallurgy, or alternative methods and is currently being undertaken on a small scale in Victoria (Xu et al. 2008). Technical challenges exist regarding the separation and purification of the plastics, copper and aluminium foils, as these still represent valuable waste streams and would contribute to the economic feasibility of processing.

Similarly, there is potential for the recovery and regeneration of electrolyte salts used in LIB. Previous studies have focussed on the extraction of electrolytes into organic solvents, such as ethanol or isobutylalcohol immediately following the sorting and dismantling process and prior to further processing to recover the metals. Furthermore, the recovery of electrolyte solutions could also allow the metals contained within the cathode to become more amenable to leaching, as the solvation would simultaneously dissolve the polyvinylidene fluoride (PVDF) binder materials that are used for linking the cathode and aluminium foils together (Xu et al. 2008).

Generally, in metal recovery processes for fine cathodic powders, graphite is considered to be an impurity and the focus on recycling process is primarily on the recovery of metals (Li et al. 2016). As graphite is a relatively inert material, it has the ability to withstand harsh processing conditions, there is the potential to be recovered prior to or after metal recovery and this could supplement the use of naturally-occurring graphite for many technical applications (Zhang et al. 2017). It was also suggested that the graphite can be used as a reducing agent to facilitate the recovery of metals during hydrometallurgical processing (Li et al. 2016). More recent research has suggested that the graphite can be recovered from electrode powders, and converted into graphene (Zhang et al. 2017).

7.4 Technical challenges for LIB recycling

Technical challenges are generally a result of the complex and heterogeneous nature of the wastes, the generation of toxic emissions, or the loss of some lower value metals from processes (Pagnanelli et al. 2016; Zeng & Li 2014; Xu et al. 2008). It is apparent from the literature that the technical development of processes associated with the recovery of resources is not as challenging as addressing the front end logistics of a waste management process dedicated to lithium ion batteries in Australia. Though it is likely that the dominant chemistry types of LIB will change as innovation and technical development of new battery materials progresses, it is likely that these factors would it will mostly impact the pre-processing and process optimisation of and the economics associated with the types of materials recovered, and not the type of process implemented for recycling.

7.5 Battery reuse

7.5.1 EV to Energy Storage

Much of the focus of end-of-life batteries is that of recycling. However, one step above recycling in the waste hierarchy (Figure 12) is reuse, as this is an improved use of precious resources with better environmental outcomes. It is widely accepted that once EV batteries reach a point of end-of-life within vehicles, they may be used for energy storage (Gaines 2014; Ahmadi et al. 2014), sometimes known as 'second life' batteries. Most manufacturers are partnering or independently exploring energy storage solutions for their vehicle batteries for example, Nissan and Eaton (Vaughan 2017), Renault and Powervault (Renault 2017) and BMW.

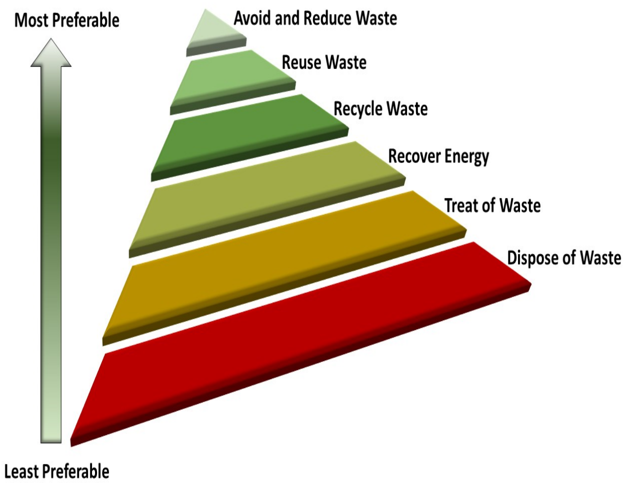

Figure 12 Waste Hierarchy.

The reuse option is linked with forecast growth in the EV market, and continual and steady access to end-of-life batteries from this sector. Due to the high energy and power requirements of transportation, a LIB is deemed to have reached end-of-life when it approaches 80 % of its initial capacity and can no longer provide the required energy for vehicles. However, for alternative applications, some of the remaining capacity could still be utilised as their requirements are lower than those of transportation. One 2016 market research report forecasted that by 2025, 29 GWh of used EV batteries will become available. Of this, approximately 10 GWh will be available for second life, stationary storage applications (BNEF 2016). It is likely that repurposed EV batteries will be cheaper than new energy storage batteries. However, there will be trade-offs to consider such as testing, certification to a shorter life time than new batteries and addressing consumer concerns or biases against a second life product.

Hong Kong has government incentives to encourage and support the adoption of EV, such as tax incentives, implementation of EV charging infrastructure, support for EV public transport and government procurement of EV. Coupled with forecasted growth of EV, the government is also supporting technology ideas for EV to energy storage. The Hong Kong government anticipates such a demand for this solution that they have run a competition for the best ideas to convert EV batteries to energy storage technology (Government of Hong Kong 2017).

As previously mentioned, the current adoption of EV in Australia is low and it is anticipated that EV on the road will continue to increase and is forecasted to reach 425,000 by 2030 (Asghar 2016). Recent media announcements have shown a trend towards the adoption of solar and large-scale grid storage batteries in Australia. For example, the 100 MW storage project in South Australia is a strong signal that energy storage solutions are gaining traction within Australia.

One Australian company seeking to capitalise on this opportunity is Relectrify, which is a Melbourne-based start-up company seeking global opportunities in the area of battery reuse and second life batteries. Relectrify technology optimises second life battery operation for EV to Energy storage solutions. Relectrify were recently a finalist for the 2017 Hong Kong second life battery competition.

One of the challenges with the application of second life batteries is the lack of policy and protocols or certification around the reuse of batteries for energy storage. Currently, consumers cannot be assured that second life batteries will provide a standard and reliable life span, or are supplied from a certified and reliable manufacturer or distributer. Similarly, there is a question of how car manufacturers can be assured that their end-of-life battery product has been re-purposed with a reliable reuse opportunity, and that the waste product from second life batteries are adequately handled and disposed. Irrespective of these concerns, the increasing recognition of the opportunity to reuse batteries by car manufacturers will continue to support this opportunity. As in the future, the number of EV on road and their subsequent end-of-life batteries will also increase. This option is a viable future opportunity, and the comparative life cycle for traditional versus reuse is shown in Figure 13.

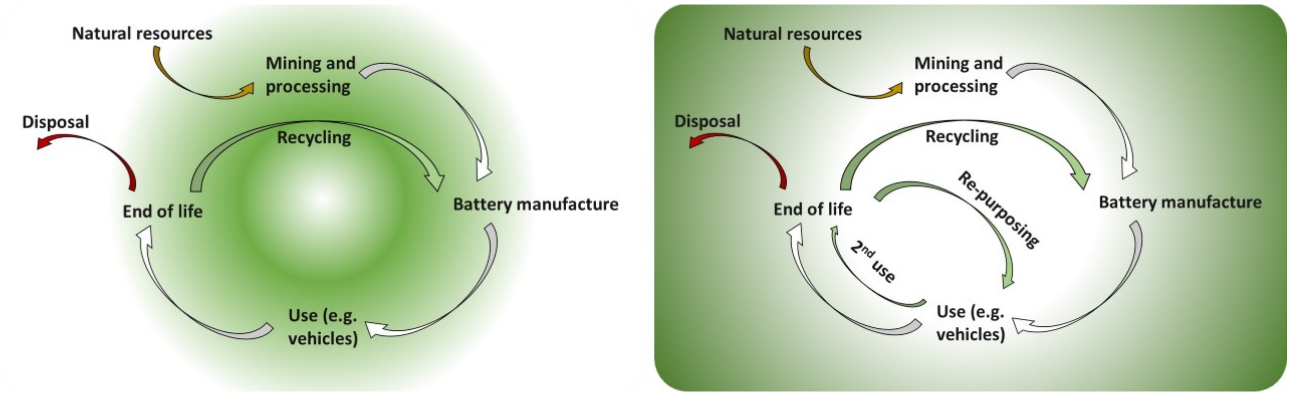

Figure 13: Traditional (left) and reuse (right) life cycles for LIB (reproduced from data in Ahmadi et al. 2014).

7.5.2 Battery rejuvenation research

Novel scientific research into lithium battery rejuvenation or re-manufacture is currently being investigated (for e.g. Wang et al. 2011; Gies 2015; Liu et al. 2016). For example, one process involves "bathing the cathode in a soft chemical solution to rejuvenate it". This process is presented as being more cost effective than battery recycling, as it prevents the cathode from needing to be rebuilt and retains materials in their original form (Gies 2015).

Battery cell rejuvenation or re-manufacture seems to be an overlooked research and development area as it is presumed that once a product reaches end-of-life, the next logical step is to move directly to processing or recycling. There are also complexities with disassembly which could be addressed by improved battery design and packaging to support battery rejuvenation.

The key scientific challenge is the removal of degraded materials and also removal of the solid electrolyte interphase layer. This is formed during cycling from breakdown of electrolyte materials which serves to protect the electrodes. As the SEI layer increases in size, the beneficial properties are reduced and batteries start losing performance and capacity, eventually leading to cell end-of-life.

A simpler rejuvenation concept is replacement of entire cells which have degraded in a larger battery pack systems. A direct swap out with new cells could in principle prolong the overall battery pack lifetime where degradation or failures due to a few cells have occurred rather than all cells failing. This concept requires that battery packs and systems be designed and constructed to enable this form of "servicing" to occur.

Generally speaking, the best use of resources from a material and energy efficiency perspective is reuse, before recycling. This delays end-of-life processing and prolongs the life of a cell, therefore extending the original product life beyond the original manufactured timeframe. This research area is indeed challenging but deserves attention by industry, policy stakeholders and the research community to attempt to retain resources in the productive economy for as long as possible. The rejuvenation example and EV to energy storage are examples of this approach.

8 An international drive for resource recovery from LIB

The development of technology for resource recovery from LIB wastes in other countries around the world has largely been driven by policy and regulations that ban landfill disposal (of all wastes in some countries, like Germany), set resource recovery targets from specific waste streams and provide incentive or penalty to manufacturers and distributers when they are not achieved. These regulations, targets, incentives and penalties drive innovation for technology development. The waste management and product stewardship landscape are in transition, with more focus on priority waste streams, and diversion of these from landfill. Unfortunately, Australia by comparison does not have as comprehensive policy and regulation that specifically addresses LIB or LIB waste and infrastructure specifically for LIB recycling in Australia is absent. This chapter reviews the international regulatory landscape and compares it to that in Australia.

8.1 International regulations for resource recovery

In terms of global transport, LIB and LIB waste is classified as Dangerous Goods. Despite this, there is significant country to country variability in the environmental management of end-of-life LIB, and this is supported by a raft of policies and regulations that differ from country to country. European countries such as Germany are the most advanced region in tracking, capturing and diverting all wastes (including e-waste) from landfill, while Korea imports e-waste and other wastes as a resource, focussing more on the development of an economically viable recycling industry.

8.1.1 Europe

A number of internationally recognised treaties and conventions, including the Basel, Stockholm, and Rotterdam Conventions, have been ratified to control the movement of hazardous wastes across borders, with some specific references to the control of handling, distributing, movement and treatment of e-waste and waste batteries. For the most part, these conventions regulate the movement of hazardous wastes from developed countries to less developed countries, where costs associated with disposal and treatment are lower, and regulations surrounding the disposal and recovery of resources from these wastes may be less developed and more flexible in their application.

In order to promote resource recovery and closed loop processing for new LIB using recovered materials, regulations and policies now exist in parts of the world that control the handling, disposal, management and recovery of resources from e-wastes, including LIB waste. The most significant legislation is the Batteries Directive, which was introduced by the European Union in 2006 (Directive 2006/66/EC of the European Parliament and of the Council). This directive was intended to protect, preserve and improve the quality of the environment by reducing the increasingly negative impact of batteries and accumulators, as well as the waste batteries and accumulators that are produced.

The Batteries directive had the following mandates:

Collection rates had to reach 25 % and 45 % by 2012 and 2016, respectively;

- Recycling of battery and accumulator content to produce similar products or for other purposes was to be 65 % (by weight) for lead acid batteries, 75 % of nickel-cadmium batteries and accumulators (including as much lead recycling as feasible from these), 50 % of all other battery and accumulator types;
- Prohibition of disposal of industrial/automotive batteries/accumulators to landfill or incineration; and,
- Allowing the recycling and treatment to happen outside EU, provided EU legislation for transport/transfer of hazardous waste was followed.

Reports indicated that the 2012 targets were met by most EU members, but the 2016 target was too ambitious, with definitions being a bit subjective and measuring tools not providing accurate data (Recycling International 2013). In 2014, only 7 member states had achieved the 2016 target of 45 %, and four member countries were yet to reach the 2012 target of 25 % (EUWID Recycling and Waste Management 2016).

8.1.2 United States of America

In the USA, LIB are considered to be hazardous and are regulated under the Standards for Universal Waste Management (Electronic Code of Federal Regulations, Title 40, Part 273, US EPA). This regulation mandates that waste batteries can be collected as hazardous wastes for further treatment and/or recycling, and prohibits the disposal of some nickel-cadmium, mercury-containing and small, sealed lead batteries to landfill, instead encouraging the recycling of these particular batteries. However, the Federal Government standards do not include any directive targeted at resource recovery from LIB waste, with some states in the USA developing their own state-based regulations that enforce producers to offer or fund battery recycling. These schemes are active in California, Minnesota, Iowa New York, Florida, Vermont, New Jersey and Maryland (Call2Recycle USA 2017). In addition to these, most states have regulations focussed on the recycling of lead acid, small nickel-cadmium and other batteries that are regulated at the Federal level for disposal (e.g. Texas, Utah, and Michigan).

8.1.3 Canada

In Canada, extended product stewardship regulations exist in British Columbia under the Environmental Management Act (Recycling Regulation; B.C. Reg 449/2004), which mandates that obligated parties (manufacturers, sellers/distributers and importers) must have an approved product stewardship plan in place in order to prevent pollution due to the production of wastes, including primary and rechargeable batteries (Schedule 3, Electrical and Electronic Product Category). The Act called for a total recovery rate of 75 % of all goods defined, and as a result of the Act, Call2Recycle set increasing targets for battery recovery, from 12 % in 2010 to 40 % in 2012 (CM Consulting 2012). The other Canadian provinces have hazardous material product stewardship regulations in place, but none of them mandate recovery targets. Though the regulation is specific to British Columbia, Call2Recycle Canada operates an approved product stewardship program in all Canadian provinces (Call2Recycle Canada 2017).

8.1.4 China

China us the largest consumer of electronics and produces the highest number of LIB when compared to other developed countries. However, regulations for the management of LIB waste are not very well developed, and as of 2015, no national or regional regulations existed to promote the recovery of resources from LIB waste (Zeng, Li & Liu 2015). In 2017, China announced a general ban on global imports of waste products into the country (Lasker et al. 2017). The full impact of these import bans is yet to be seen, but it is already having an effect on the global waste management industry, resulting in a push for more detailed waste and materials tracking, improved collection and sorting, and innovation for local recycling and resource recovery from all wastes, including LIB waste.

8.1.5 Japan

In Japan, the Law for the Promotion of the Effective Utilisation of Resources (2000) mandates that rechargeable batteries are classified for recycling at the manufacturing stage using a standardised three arrow recycling mark indicating battery type and primary metal components. When they reach their end-of-life, these marked batteries are then collected and recycled appropriately (Battery Association of Japan 2010a). The Law also sets a LIB recycling target of greater than 30 % and stipulates that all manufacturers and importers of batteries must have a recovery system for waste products. The Japan Portable Rechargeable Battery Recycling Centre (JBRC) was formed as part of the Battery Association of Japan to provide free collection and recycling of portable rechargeable batteries sold across the country (Battery Association of Japan 2010b).

8.1.6 Korea

The People's Democratic Republic of Korea is a leading manufacturer, exporter and consumer of LIB, being home to both Samsung and LG Chem who are the largest battery manufacturers in the world (Chung & Sungwoo 2011). However, Korea has limited natural mineral and energy resources, and as such relies on the trade of waste, importing wastes from other countries and utilising secondary resources to drive their resources industry. Imported waste (regardless of its classification) is regulated by the Act on Transboundary Movement of Waste and its Treatment (ATW), which outlines the domestic implementation of the Basel Convention in Korea. The import and export of various waste streams are recorded by Import/Export Approval and Declaration Systems (IEAS and IEDS), which are regulated under the Act on Waste Management (AWM). In the early 2000s, the primary waste imports for Korea were waste batteries, waste cable, lead scrap and sludge (3,862 tonnes over 6 import transactions). However, the volume of imports has grown substantially, with 1,338,140 tonnes of waste imported in 2008, primarily consisting of waste batteries (including nickel-cadmium, LIB and lead acid batteries) and printed circuit boards. The increase in trade volume underpins the development of regulation in waste trade for Korea, as well as the revision of both the ATW and AWM (Chung & Sungwoo 2011). Similarly, this increase in import volumes has driven technology development and business opportunities surrounding the recovery of resources from waste products, and as such, Korea is leading in the field of resource recovery and the utilisation of secondary materials.

8.2 Australian policy, regulation and stewardship schemes

8.2.1 Product Stewardship Act, 2011

In 2011, the Federal Government Product Stewardship Act was established as a means of managing the environmental, health and safety impacts of products outlined on the approved product list, specifically focussed on the impacts surrounding the disposal of these products. The Act acknowledged the shared responsibility for managing wastes and their impact throughout the product life cycle, and put in place a framework of voluntary (through industry self-regulation and government influenced quasi-regulation), co-regulatory (whereby industry develops and administers its own arrangements, but government provides legislative backing to enable the arrangements) and direct government regulation of product stewardship guidelines to promote recycling and recovery of value from waste products.

Waste lead acid batteries and e-waste from televisions and computers are both collected and recycled under co-regulatory agreements as defined by the Act, known as the National Television and Computer Recycling Scheme (NTCRS). In 2016, the Department of Energy and Environment (DEE) included battery waste, photovoltaic cells and e-waste from other sources not currently included in the NTCRS on the Approved Product List of the Product Stewardship Act (Department of Energy and Environment Australia 2016). However, at time of writing it is yet to be detailed how the product stewardship of these wastes will be developed or regulated.

Product stewardship for waste batteries and e-waste also occurs at a State and Local Government Authorities (LGA) level in Australia. Many states have their own regulations and rules pertaining to the collection, transfer and recycling of e-waste and batteries. However, the development of mandatory resource recovery programs is still in its infancy. Previously, State Governments managed their own e-waste collection programs, but the programs such as the Western Australian Transitional E-waste Program (WA Waste Authority 2014) were replaced with the NTCRS, which prohibited the disposal of some computer and television-derived e-wastes to landfill and now controls the management, diversion and recycling of these wastes at a Federal level. South Australia is currently the only State Government that completely bans the disposal of all e-waste types to landfill (Zero Waste SA 2017). In 2015, Victoria was discussing the implementation of a landfill disposal ban for e-waste (DELWP 2015). In New South Wales, the Environmental Protection Agency (EPA) and Environmental Trust funded innovative research targeting the development of new recycling infrastructure solutions and establish the recycled materials market in the state through research and development, with specific focus on the recycled and recovery of value from problem wastes such as e-waste (NSW EPA 2017). Western Australia has few regulations developed with regard to e-waste management, but a voluntary program called the Hazardous Household Wastes program enables residents to drop off unwanted household chemicals and hazardous wastes (including some kinds of batteries) at no charge. However, this program specifically excludes e-wastes and waste LIB (WA Waste Authority 2017).

8.2.2 Classification of LIB and batteries

LIB and their waste pose significant risk to safety and human and environmental health if not handled, managed and disposed of in a correct manner. Postage and shipping of LIB or LIB that are contained within a device are subject to the International Air Transport Association (IATA) Dangerous Goods Regulations. They must be packaged and labelled appropriately. All courier companies (e.g. FedEx, Australia Post) have detailed instructions pertaining to safe transport of LIB. International packages are subject to the IATA Dangerous Goods Regulations. Road transport is subject to the Special Provision 188 of the Australian Code for the Transport of Dangerous Goods by Road and Rail. This provision limits the number of batteries per package, and outlines packaging and labelling requirements.

8.2.3 Self-regulation by industry

MobileMuster is one of the largest Australian examples of a voluntary regulated recycling program. A levy is added to each phone sold in Australia, giving manufacturers some responsibility for product stewardship for mobile phones at the end-of-life. One big threat to this model is 'free riders', where brand owners are not members of MobileMuster but their phone models are able to be collected by MobileMuster and are effectively subsided by other member brands. For example, Apple never joined MobileMuster in Australia, instead relying upon their own recycling initiatives. Sony and LG have both left the program in recent years and this contributed to decreased revenues to MobileMuster, decreasing by $1.67 million between 2007-08 and 2014-15 (Read 2015).

ABRI is a not-for-profit entity and established in 2008 as the peak body in Australia for working with industry, government and the community to promote and eliminate batteries being disposed to landfill. ABRI is working to improve the collection, infrastructure and policy agenda for battery recycling in Australia (ABRI 2017). However, to date, battery manufacturers, recyclers and government have not managed to implement a similar program to MobileMuster for the collection and recycling of LIB. Handheld batteries were listed on the 2013-14 product list of the Product Stewardship Act 2011 as a priority product for development of stewardship arrangements (O'Farrell et al. 2014). An ABRI-led handheld battery implementation working group continues to scope a voluntary and industry led product stewardship scheme (O'Farrell et al. 2014). To date, an agreed scheme is yet to be implemented but has State and Territory support evidenced by a 2017 meeting of Australia's Environment Ministers which resulted in agreement to consider battery stewardship approaches which may involve a regulatory option to support a voluntary battery recycling scheme (Australian Government 2017a).

Part III

Drivers for a developing industry

Identification of gaps, challenges and opportunities through the eyes of the stakeholders

9 Methodology

In order to better understand the status, direction and challenges for LIB battery recycling in Australia, CSIRO contacted and interviewed six key stakeholders with roles associated with end of life LIB. Through formal stakeholder interviews and informal engagement by author attendance at industry workshops, conferences and other industry events, qualitative data was gathered to determine stakeholder perspectives relating to the challenges and opportunities for Australia in developing an onshore recycling program for LIB waste.

The semi-structured, qualitative interviewing was undertaken in an inductive approach to uncover topics most frequently cited and strategic themes that may not be adequately covered by the literature (Williams & Lewis 2005). Interview data was captured in 2017, with ethics approval from the CSIRO Ethics committee. As there were a relatively low number of interviews captured, it may not be possible to generalise the research findings across the entire sector. However, interviewing is a high-quality data capture method and these findings represent information from battery end-of-life stakeholders within Australia. While the count of interviews is small, it is important to recognise that the Australian LIB recycling sector is small and the interviews capture 43 % of the LIB recycling and collection industry, based on the ABRI website list of industry participants (ABRI 2018). In addition, to counter the low number of in-depth industry interviews, the captured data was complemented by discussion with stakeholders as part of CSIRO's broader industry engagement. This provides a more generalised information baseline. All industry feedback has been de-identified in accordance with CSIRO ethics approval.

Interview data was initially captured in note form, then major points were coded into PESTLE categories (Political, Economic, Social, Technical, Environmental and Legal), further coded to indicate either a positive or negative overall business impact. PESTLE analysis is most useful for strategic analysis where the lead driver is to understand the external environment. An example of the PESTLE framework is shown in Table 7. Data were also loaded into NVIVO, a qualitative data analysis software package, to code and evaluate the frequency of common themes. Finally, common themes were supplemented with desktop sources literature, where required. Due to a low number of Legal items being raised, results are reported in the PESTE format; combing legal with political themes (i.e. regulation and policy).

Table 7 PESTLE Framework used for all stakeholder interviews

	Political	Economic	Social	Technical	Environmental	Legal
Opportunities (+ve)						
Business impact						
Issues (-ve)						
Business impact						

10 Policy and regulatory drivers

Interview data suggested that the lack of policy was a serious gap for reuse or recycling of LIB waste. All participants agreed that Australia had a moral obligation to directly manage its own waste and this necessitated a domestic processing option. Some participants proposed that Australia had an opportunity to be a leader in the Asia-Pacific region for battery processing, noting that New Zealand sends its batteries to Singapore for processing. However, a full assessment of economic drivers and challenges is required to support the development of the industry.

As evidenced by international examples, policy levers have the potential to radically change the nature of how Australia deals with end-of-life batteries. For example, policy to support greater adoption of EV, the provision of incentives for EV purchase, the removal of import taxes or installation of widespread EV infrastructure, would have a significant boost to the adoption of EV in Australia. This would in turn increase the stock and security of second-life and end-of-life EV batteries that would require recycling and resource recovery. In Australia batteries are identified on the product list for consideration in the Product Stewardship Scheme. This is a requirement to indicate to industry and the community that batteries are being considered for regulation or accreditation. Policy that identifies batteries as a priority waste stream or banning batteries going to landfill would also result in meaningful increases to stock levels. However, as one participant noted, landfill bans could also result in an increase of illegal dumping and subsequent contamination of the environment or risk to human health.

Interview data also suggested greatest support for a voluntary program, modelled on the successful MobileMuster program for mobile phones. This option is also the cheapest for government, rather than managing a fully-regulated recycling scheme. Participants suggested that handheld batteries are the most likely initial LIB product to be managed in a scheme.

10.1.1 Australian standards, certifications or protocols

There are a lack of standards or protocols in a number of areas for LIB, and this is a concern for all stages of the life cycle. When importing, consumers presume that products containing batteries are fit-for-use. However, there are a number of 'aftermarket' brands (i.e. products manufactured after the sale of the original product) that may be of a lower quality with poor performance and higher safety risks associated with them than more reputable brands. One of the improvements following the 'exploding' battery issue associated with Samsung products, was the recent announcement of a new 8-point standardised battery testing protocol. Samsung also made their battery testing protocols publicly available (Samsung 2018).

There are gaps in international standards for testing or certification of batteries in consumer products. Examples of protocol gaps presented by participants were standard protocols for battery testing, certification of battery quality and fit-for-purpose, certification of batteries for reuse (such as EV to home storage), certification of EV batteries for reuse following a vehicle crash, protocols for attending LIB fire (home or vehicle), and protocols for safely discharging of batteries at end-of-life.

Similarly, the gaps in of standards also makes second-life, reuse, recycling of and resource recovery from these batteries more difficult, where quality and safety of re-manufactured batteries cannot be verified, and discharging of batteries prior to processing is not standardised.

The lack of testing and certification protocols presents consumer and business risk and safety concerns. However, it also presents an opportunity for companies to fill the gap by developing and testing against Australian protocols.

11 Economic considerations

Interview participants noted the important role of product owners or importers for the responsibility for battery waste at end-of-life. Most participants suggested that as manufacturers were the original owners of the product, and therefore the originating cause of Australia's landfill problem and future liability, they should pay for recycling at end-of-life or include recycling treatment costs in their product pricing. This concept of product stewardship has increasing acceptance following the implementation of the Product Stewardship Act in 2011. Involving manufacturers in addressing end-of-life processing is also the model that has been implemented for mobile phones in Australia. Therefore, the concept of OEMs being responsible for the management of end-of-life products has a precedent.

11.1 Transport Costs

Other economic issues raised by the participants were the costs associated with the import and export of battery waste. Export permit costs are increasingly viewed as prohibitive despite the Department of Environment stating that fees are set solely by the time required to process an application. The expense of export permit licences was approximately $ 8,000, increasing to $ 13,000 as of 1 July, 2017 (Australian Government 2017b). The cost of import permits is a deterrent to Australia processing regional LIB waste even though there is potential to import from Asia and Pacific Islands, including New Zealand. This is a barrier to Australia becoming a regional LIB processing hub as it builds infrastructure to process domestic waste. One participant noted (as at 2017) it is currently cheaper for batteries from New Zealand to be sent to Singapore than to Australia.

11.2 Security of supply

Security of waste supply was also a driver for considering the economics associated with developing a local LIB recycling industry. Currently, Australia only produces a relatively low volume of LIB waste, and in combination with poor collection rates (less than 2 %), the economic feasibility of processing options was questioned by participants. It was generally acknowledged that social issues, such as the lack of collection infrastructure and community awareness of where to take end of life batteries, is the primary cause of a lack of sufficient volumes and ongoing supply of waste feedstock. This has a big impact on the market subsequently not being ready to invest in infrastructure. If the available stocks were collected for recycling, as opposed to being sent to landfill, then this would result in industry having confidence to invest in processing infrastructure.

11.3 Loss of potentially valuable resources

Participants also noted the potential valuable resources arising from battery waste including metals, plastics and graphite. It was suggested that some raw materials arising from battery processing are not available here in Australia, and there was recognition that some of the secondary materials recovered from LIB waste may be able to find niche manufacturing markets.

11.4 The high cost of collection and transport

In addition to low waste volumes, the cost of collection and transport have also been identified as a major contributor to the economic feasibility of domestic processing, especially in Australia which consists of small, widely dispersed population centres. Through visiting our South Korean counterparts in mid-2017, it was noted that in South Korea the collection and transport of e-waste and spent batteries contributes up to 50 % of their overall processing costs. High domestic transport costs are a driver for developing mobile processing infrastructure for Australia. There was strong support by participants for Australia to develop and implement mobile processing infrastructure as this is the most suitable for Australian conditions.

In addition to the complexity and heterogeneous nature of the waste, the requirement for, and cost of, manual handling and sorting of the battery waste also presents challenges for recycling this waste. The consistent and constant supply of the waste product for processing, variability in commodity prices, as well as the cost of collection and transport of waste to the processing facility each also influence the feasibility of realising increased domestic processing.

11.5 Economic modelling and information gaps

It was acknowledged by the participants that industry would always seek the lowest cost processing option, and currently the benchmark is the export market price for processing. During the interview process, it was suggested that economic modelling of options to understand the impact of various policy and socio-economic levers would be very useful in understanding the correct approach for Australia. Defining what happens to LIB waste volumes under various conditions such as ban of exports by no longer issuing export permits, all batteries exported for processing, or implementation of a full LIB Product Stewardship scheme, would help to address knowledge gaps. This type of economic evaluation would better inform industry stakeholders prior to investment in this developing industry.

12 Social Considerations

Much of the end-of-life battery stock collected in Australia is exported for recycling. The issue with global recycling is that waste can potentially be exported to developing countries with less stringent social and environmental controls for processing wastes. All participants were unanimous in stating that Australia had a moral obligation to process its own waste. All participants believed that LIB waste would eventually be processed domestically. However, a key challenge for Australia to improve the recovery of LIB wastes and diversion from landfill is the lack of consumer awareness of the environmental damage LIB waste can cause, and where LIB can be dropped off for recycling. Currently, some retail companies accept lithium batteries for free, but this is not well known amongst consumers.

12.1 Consumer behaviour

Amongst interview participants, the lack of consumer awareness of recycling opportunities was stated as the single most important barrier preventing increased collection of end-of-life batteries. Consumer education of the environmental impacts of batteries, the importance of not sending batteries to landfill, and available options for recycling are some of the biggest hurdles for the battery recycling sector. The current option for disposal of LIB is currently free, whereby consumers can place this waste in a municipal waste bin. Any future collection and recycling options may involve a cost and placing the recycling cost onto the consumer will be a further barrier for collection at end-of-life. Coupled with a likely ban of batteries to landfill, these factors may result in illegal disposal of batteries which is highly undesirable due to the environmental and human health risks that incorrect handling and disposal pose.

MobileMuster has had a big focus on addressing consumer education of their mobile phone recycling options. Their efforts have comprised of working with schools, social media campaigns and working with charities to increase the number of mobile phones being collected and recycled. As a consequence of their efforts, fewer people are disposing of their phones to landfill. Over the ten-year period from 2005-2010, the proportion of landfilled mobile phones has decreased from 9 % to 2 % (Read 2015). This has been achieved through a dedicated program of education, coupled with freely available disposal units dispersed across the country. Mobile phone stockpiling remains a problem with 40-60 % of people stating they retain their phone as they would like a spare or backup phone. Despite this challenge, there has been a small increase in the likelihood of people recycling their old mobile phone from 25 % to 35 % since 2006 (see Figure 14).

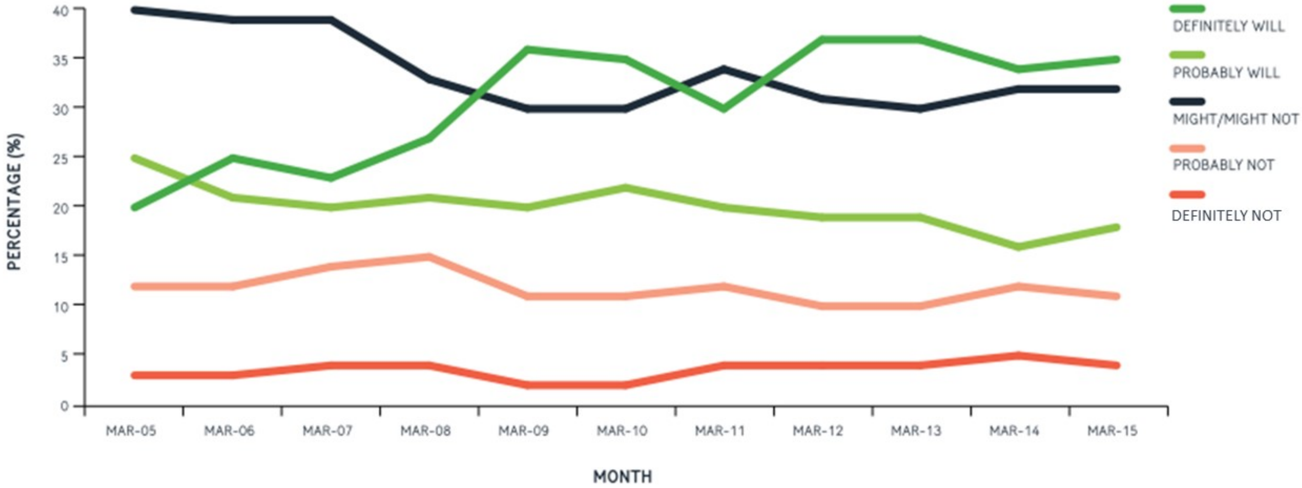

Figure 14: Likelihood of recycling a mobile phone (Read 2015, p.32)

12.2 Industry guidelines - transport

The participants acknowledged that there is a need for plain language, best practice guidelines for the transport of end-of-life LIB, applicable to the Australian market. Domestic transport is currently required in Australia to collect batteries for export or onshore processing. The interviews revealed that different recyclers have different interpretations of transport rules. For example, some companies wrap the entire battery in tape to protect the anode and cathode during transport in an attempt to reduce the risk of fire or explosion, whereas other companies do not. Both the packaging and downstream processing are labour intensive and costly. Compounding this issue is inconsistent labelling of battery types during domestic transport. This is evidence of an emerging market where consistent processes have not yet been implemented across the industry. The issue of confusion from the transport industry on safe road travel for end of life LIB was also noted in a recent report (Lewis 2016). These issues are likely a consequence of low levels of LIB waste currently being captured. However consistent and safe domestic transport practices will become increasingly important as Australian e-waste landfill bans are rolled out across Australia, higher volumes of end-of-life LIB are collected and domestic facilities upscale and commence processing larger quantities of LIB.

13 Technical Factors

A number of technical factors were raised as a result of discussions with participants, including practical issues such as safe discharge of batteries prior to processing or transport for export, and adequate labelling to ensure the proper handling of batteries. Many participants supported the idea of mobile processing facilities suitable for Australia's distributed population, but suitable technology for LIB recycling in Australia has yet to be determined.

13.1 Labelling

The difficulty of identifying LIB chemistry due to a lack of adequate industry labelling was noted by most industry participants as a major concern for safety and processing. Although there was some difference of opinion here, some participants agreed that improved labelling would help with sorting. However, as there are currently no industry standards, recyclers need to adopt alternative and boutique practices to sort batteries. It was also acknowledged that given the long service life of some batteries, physical labelling would need to withstand an in-use period, and this may present challenges to OEMs. Sorting is currently possible under existing labelling conditions and this was an issue that could be successfully managed by adequate staff training to recognise different battery chemistries. For example, all batteries carried clear voltage labelling and battery chemistry could be deduced from voltage or battery product shape and size. In the absence of suitable labelling, training and education was currently overcoming this problem in the short-term. Labelling may not be an acceptable solution for larger scale collection and processing.

13.2 Fire and Safety Risk

The safety and fire risk associated with the transport and processing of batteries was acknowledged by most participants as a key issue. There have been a number of in-use and transportation aviation fires (Cavanagh, Behrens, et al. 2015) and LIB can cause fires even when disposed to landfill (O'Farrell et al. 2014; Heelan et al. 2016b). LIB have been known to be accidentally mixed into the lead acid battery recycling stream as a result of the lack of clear labelling. Once LIB reach the input stream of lead smelters, this poses a serious danger and has resulted in fires and explosions. This can occur as a consequence of mixed loads of batteries delivered to recyclers, but the risk could be reduced if there was an economic incentive for processing LIB, which would promote collection and sorting prior to processing (Gaines 2014). It is imperative that the potential contamination of recycling streams is addressed. An effective labelling or sorting process would address this issue which extends responsibility back to battery manufacturers for appropriate labelling, to the regulatory bodies to enforce standardised labelling, and to recyclers for implementing an adequate sorting system.

One participant raised the example of a significant fire in the Port of Colombo in Sri Lanka that was attributed to Australian LIB cargo en route to Belgium for processing. This spontaneous fire burned for 5 days before it could be extinguished. The investigation report has resulted in the shipping company involved in the incident no longer accepting waste or recycled LIB for transport (BEA Mer

2017). This outcome could have major repercussions for global shipping transport as options for freighting end-of-life batteries may be significantly reduced due to the potential hazard and fire risk threat of LIB. The safety and fire risks also have the potential to impact on Australia as it is possible that new regulations or decisions by transport companies to no longer accept waste LIB may force Australia to process LIB domestically rather than continue to rely on export for processing.

13.3 Battery discharge

Recycling of LIB presents unique safety and handling issues. If LIB are stored without proper discharge, there is potential for them to short circuit unintentionally which would potentially lead to a fire. It is important that LIB should be discharged or decommissioned by a trained and licenced personnel (Lewis 2015). An alternative deactivation approach is a thermal pre-treatment where batteries are heated to a maximum of 300 degrees. This opens the battery cells and combusts solvents which renders the battery inactive (Diekmann et al. 2017). As referenced by a stakeholder participant, the discharge process is even more cumbersome for compromised EV LIB where one industry guideline recommends soaking the entire vehicle up to tyre height in a bath of water for 72 hours. This results in potentially dangerous hydrogen emissions and the treatment water becoming industrial waste (Mitsubishi Motors 2013). This example illustrates why improved methods and procedures for discharging EV batteries are desirable. Moreover, a standardised pack construction method that allows simple disassembly at end-of-life is also desirable.

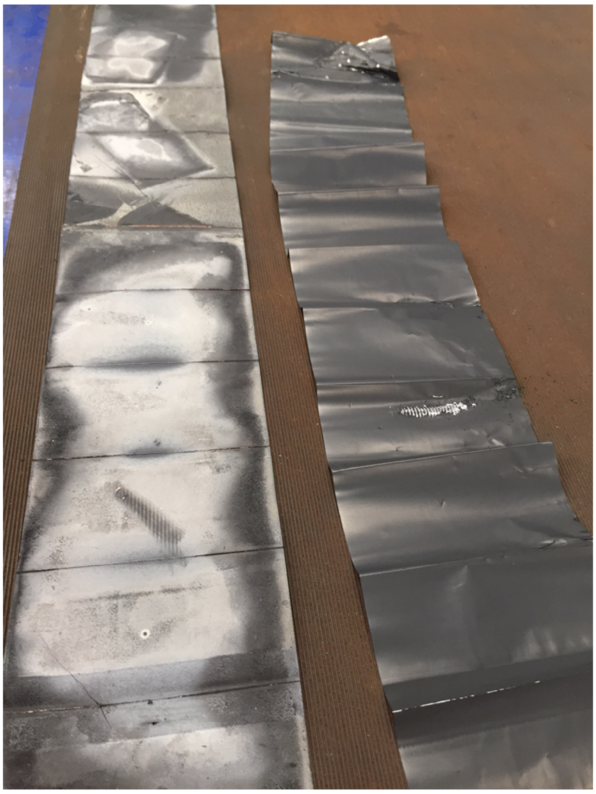

Figure 15: Typical LIB "Jelly Roll" unwrapped showing graphite anode (left) and cathode (right). Underlying copper foil (left) and aluminium foil (right current collectors can be seen where coatings have been removed during disassembly.

13.4 Pre-processing of batteries

Following their discharge, pre-processing of the batteries is required prior to the recovery of the valuable components. This pre-processing consists of sorting into similar battery chemistries then separating the graphite and lithium cathode from the copper or aluminium material.

Figure 15 shows an unwrapped "Jelly Roll", where the anode is on the left with copper and a graphite surface. The cathode of aluminium with the NMC or LCO coating is positioned on the right. Given the anode and cathode are manufactured so the graphite and lithium-based materials remain fixed to the electrode, separation of these materials from the metals is a technical challenge, and this was identified by some of the interview participants. Improvements in the separation of materials to develop a pure resource stream from a pre-processing treatment process would directly improve the economic benefits of recycling.

13.5 Circular economy

There is growing interest in the various business models provided by the circular economy for Australia. A recently published South Australian report estimated the circular economy would result in an increase of 25,000 jobs and a 27 % decrease in greenhouse gas emissions by 2030 compared to a business as usual scenario (Lifecycles 2017). Lithium mining in Australia is an emerging area with good growth prospects. There have also been media reports of a proposed lithium battery factory in Darwin (Daly 2017).

Recycling companies could explore partnerships with mining companies to ascertain any complementary infrastructure or capability. This is the proposed approach one mining organisation in WA is in the process of undertaking. Moreover, the production of any value-added products by

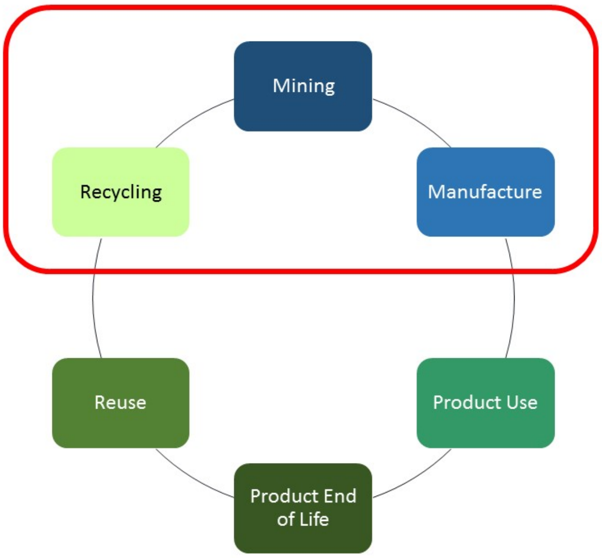

Figure 16: Potential circular economy model for lithium batteries.

recyclers for manufacturers is another opportunity. These are examples of connecting three sectors of LIB recyclers, lithium miners and advanced manufacturers (Figure 16) and these upstream and downstream supply chain connections are a key part of commencing circular economy discussions and identifying further value add opportunities from LIB waste in Australia.

13.6 Distributed waste processing

The rise of the circular economy supports new opportunities with alternative business models. The distribution of waste across Australia results in collection issues, the chief of which is the cost of logistics and transport of waste for processing. To directly combat the high transport costs, Australia could adopt a mobile, flexible, small scale recycling process. In this model proposed by participants, waste discharging, sorting and dismantling could occur locally, and the processing infrastructure could travel to key locations across Australia, instead of the waste resources travelling to key infrastructure sites. The success of such a model would still require certainty in the collection and local stockpiling options for LIB during periods when the processing infrastructure is absent. Alternatively, having a larger processing facility with the capacity to do both local and international LIB recycling could help offset local transport costs.

If there is greater availability of processed resources within Australia, this then enables a truly closed loop manufacturing process to occur with the domestic utilisation of recovered metals and resources rather than export of waste and import of resources or products. There is potential for a disruptive processes or technologies such as additive manufacturing to be a trigger for utilising recovered resources from waste products, and equally enable small-scale, distributed manufacturing within Australia (Giurco et al. 2014). These strategies are examples of the circular economy in Australia.

13.7 Lack of information and data

Participants suggested that there was not adequate data available which would support investment into infrastructure. Certainly, there is a lack of adequate data for the waste sector making this complaint understandable. Furthermore, the recycling industry has not had a history of investment in research and development to the same level as mining in Australia (Giurco et al. 2014) and it is unclear if more reliable data will improve that situation. Research investment to address these information gaps has already occurred by various industry, State and Federal groups, but interview participants proposed a number of outstanding information gaps, including:

- Economic modelling and cost-benefit analysis based on scenarios for policy changes, landfill bans, export/import restrictions. This modelling will provide the recycling industry with adequate confidence in the number of available end-of-life handheld batteries;
- Life cycle assessment (LCA) on the benefits of converting end-of-life EV batteries to residential or commercial energy storage, as compared to recycling;
- Information regarding the best existing recycling technology for Australian conditions, including the identification of the best equipment for use on different battery chemistries, scale mobility and flexibility of technology, use of existing mineral processing technology, and transport and pre-processing options; and,

- A best practice guide for battery recycling for Australian consumers and stakeholders.

14 Environmental issues

During the interviews, there was little focus on the environmental issues associated with LIB waste, as it was commonly accepted that batteries pose an unacceptable environmental and human health risk when disposed to landfill. This is well-acknowledged in academic literature (Zeng et al. 2014; Aral & Vecchio-Sadus 2008). Waste LIB are currently classified as Dangerous Goods, not a hazardous waste (Randell et al. 2014), but they have the potential to leach toxic materials into the environment as well as posing fire risks if punctured or short circuited. This is then exacerbated when non-LIB are disposed into landfill where additional risks from mercury, lead or cadmium leaching into the environment/waterways also exists. There are current industry procedures to contain leaking batteries when they are detected. One participant gave an example of a compromised and leaking mobile phone battery where proper landfill disposal requires first wrapping it in a plastic bag and then containing it within concrete in order to prevent environmental damage from occurring. This onerous process is indicative of the potential hazard LIB pose to the environment. All interview participants were unanimous that landfill was an unacceptable option for batteries and Australia should adopt domestic solutions for processing end-of-life LIB.

Part IV
Summary

Conclusions and key findings

15 Conclusions and key findings

15.1 Conclusions

Lithium battery recycling is an emerging industry in Australia. Currently, less than 2 % of this waste is collected and exported overseas for resource recovery, while the majority of the waste is still disposed to landfill. As the demand for consumer and commercial products containing LIB continues to increase through the forecasted growth in EV sales and the adoption of grid and off-grid energy storage technology, Australia has an increasing social and ethical responsibility to manage LIB wastes locally, and an environmental obligation to divert these wastes from landfill, and to recover and reuse the materials appropriately.

There are significant economic drivers to support the development of an industry surrounding the recovery and reuse of valuable materials such as metals (e.g. cobalt, lithium, nickel, and zinc), graphite and plastics. In addition, LIB wastes are in the process of being banned from landfill in some Australian states. If a product stewardship scheme is implemented in Australia, these two factors will positively impact on the number of batteries collected and requiring further processing. However, the development of consumer awareness programs for LIB recycling, collection of data regarding generation and fate of LIB wastes, and standards and protocols surrounding the collection, transport, handling and discharge of LIB are key challenges for the industry.

The participant interview sample comprised of a small number of industry stakeholders operating with end-of-life LIB. This report has limitations arising from the small sample size, but the authors supplemented the information and themes garnered from stakeholder interviews with a thorough desktop review. From the desktop review and stakeholder interviews, the following conclusions regarding the development of a local recycling industry for LIB in Australia were made.

The aim of this report was to bring together various academic literature and white papers that are relevant to this emerging industry. We also wanted to include the voice of industry stakeholders in articulating the challenges and opportunities for this emerging industry. We found that while there are headline issues in each of the PESTLE areas, often they are inter-connected. For example, addressing the social issues of LIB collection is associated with economic viability of recycling due to volumes available for recycling which is in turn connected with decisions on technical processing options. Our summary of the key points for each area is provided below.

Political and regulatory drivers

The Australian policy and regulation landscape for management, product stewardship and resource recovery from LIB is developing, and each State operates their own regulatory guidance for the recycling or recovery of this waste. Some states have already commenced or are considering a landfill ban for the disposal of batteries which will result in greater numbers of LIB being diverted from landfill. Industry stakeholders supported the development of a voluntary recycling regulatory framework using proven models, such as MobileMuster, as a reference scheme. An example of an international shipping ban on carrying waste LIBs highlights Australia's waste management exposure to factors beyond our control, and this example has similarities to the China waste ban. This is a driver for Australia to manage waste streams domestically. There is also potential for Australia to act as an Asia-Pacific recycling hub, with opportunities for importing waste from regional neighbours such as New Zealand.

Economic considerations

There are considerable economic drivers supporting the development of a local recycling industry for LIB in Australia, largely driven by the value of materials that could be recovered (metals, plastics and graphite), as well as the current cost of waste export to the international market. The current collection of LIB waste is too low to support a local recycling industry for LIB, but forecasting showed that sufficient volumes will be generated in the near future (*ca*. 2036) and that this represents a significant opportunity for the Australian economy. However, there are significant gaps in data surrounding waste generation, fate and materials tracking and further consideration of the economic impacts of collection, transport, dismantling and pre-processing of battery wastes is still required. In addition, as the industry is currently very small, there is a need for further investment in research and development to shape the Australian industry.

Social considerations

One of the key barriers to the development of a local recycling industry for LIB is the lack of consumer awareness surrounding the environmental and human health and safety risks associated with improper handling, storage and disposal of LIB. In addition, the education of the consumer regarding the recycling and recovery of resources from these wastes would assist with improving collection rates, and also the sorting of materials prior to recycling. The role of the consumer is paramount in the development of this industry, and consumer education processes could be modelled on MobileMuster, as a best practice method for improving social awareness of LIB recycling. It was widely accepted by stakeholders that Australia has an obligation to process wastes locally, and this was a key driver to the development of the industry.

Technical factors

This study showed that there are a number of existing options for the processing and recovery of value from LIB waste that are available for further research and development in Australia. These processes are typically driven by the recovery of cobalt, other metals and technical materials with additional economic value from lithium recovery, and some further consideration regarding the impact of changing battery chemistries on these processes is required. In addition, further investigation is recommended into the reuse and re-manufacture of LIB, prior to disposal. There are significant technical challenges still required to be addressed for recycling processes to be efficient and these include (but are not limited to) the development of standardised protocols for labelling, dismantling and discharging batteries in order to promote efficient and safe sorting at the front end of the recycling process. The potential of mobile processing options was supported.

Environmental issues

The environmental implications associated with the improper handling and disposal of LIB waste was well-characterised in the literature and well-understood by the stakeholders engaged in this study. The stakeholders identified that consumer awareness related to this was lacking, and could be improved to support diversion from landfill and the development of the industry.

15.2 Key Findings

There is significant potential for targeted research to help realise Australia's opportunity to extract value from LIB waste. The Australian research community, in partnership with industry and governments can play a role in realising this opportunity and catalysing a new industry which in turn creates new jobs for Australia. Through the thorough desktop review and engagement of LIB battery recycling stakeholders, the following observations can be made to support the development of a domestic recycling industry in Australia.

Key Finding 1: Dedicated product stewardship programs and consumer education drives recycling and resource recovery from LIB

The lack of an appropriate product stewardship program and consumer awareness regarding recycling options for LIB are key issues that must be addressed in order to increase Australia's LIB collection rate. The current low collection rate of 2 % is reportedly limiting confidence and investment by industry into recycling infrastructure. General waste collection, transfer and management costs in Australia are costly due to large freighting distances between major population centres, without the additional impact of segregation of specialised waste streams such as LIB wastes. Introduction of a product stewardship scheme would enable rapid expansion and investment required for an expanding waste stream. Simultaneously, a targeted consumer awareness campaign and education program would help support investment in recycling processes and technology. Included in a consumer awareness campaign is to advertise existing collection sites and work towards new collection points by working with a range of OEMs, retailers and recyclers. Best practice recycling consumer guides for a range of key product ranges, such as handheld LIB, household energy storage products and EVs, would also support this effort. An education campaign also supports existing and potential future State and Territory battery landfill bans.

Key Finding 2: A safe and successful LIB recycling industry can be developed by addressing critical information gaps

Participants reported industry information gaps in best practice guides for standards regulating reuse of LIB, end-of-life transport, and recycling of LIB. Desirable information to support a successful industry included economic modelling, life cycle assessment for LIB reuse and recycling technology assessments. The collection of this information will support the safe development of an Australian LIB processing and recycling industry.

Key Finding 3: A need to identify technology processing options for the Australian context

Investment into recycling technology suitable for Australian conditions takes a modern approach to recycling. This requires the right technology and business models for an Australian context. Australia's distributed population is suitable for potential deployment of mobile processing technology. Alternatively, large scale LIB processing could also be feasible if key information and data gaps and economic modelling can be addressed. There would be a number of technical challenges that would require further research and development for both options, and this creates the potential for the development of innovative technology for the Australian LIB recycling industry. Participants suggested Australia has the potential to become a recycling hub with feedstock sourced from neighbouring countries such as New Zealand. This would further secure supply, improve economic feasibility and supports either large-scale or small-scale processing options.

Key Finding 4: An onshore, local LIB recycling industry is economically and environmentally achievable

There are strong economic and environmental drivers for Australia to manage LIB waste onshore. In this context, dedicated policies, regulations, standards and certifications relating to LIB and their waste will support technology development and industry investment in LIB recycling. Australia can view international examples such as those in the European Union and see how their existing policies, regulations and resource recovery targets have driven innovation and technology development. From this, appropriate changes can be made to provide maximum support for the Australian battery recycling landscape.

Key Finding 5: Creation of standards and industry best practice guides for LIB recycling

Dedicated standards surrounding labelling, safety, transport, discharge and processing were identified by stakeholders as key drivers for the success of the industry. Current standards need to be modified where applicable to cover LIB recycling and where required new standards would need to be written and adopted. In the interim, industry best practice guides will enable the industry to adopt new or modified standards and create a smoother transition to a new safe and environmentally sound LIB recycling process.

15.3 What is CSIRO doing in the area of LIB recycling?

Understanding that a potential need for recycling solutions will be required in the near future, CSIRO is currently exploring a number of Research Areas to provide the science needed for LIB recycling.

Research Area: Development of technical processes for recovery of metals and other materials from LIB waste

CSIRO is investigating the recovery of valuable secondary resources, such as cobalt, lithium and graphite from LIB wastes. These resources would otherwise be exported and lost from the Australian economy or lost to landfill. The research is focussed on the development of a whole process approach, which encompasses:

- Preparation and characterisation of the wastes;
- Metal solubilisation and materials recovery; and,
- Techno-economic assessment of process feasibility.

In addition, research also being conducted is targeted at defining data associated with:

- LIB waste generation;
- Materials tracking and costs associated with collection;
- Transport;
- Manual handling and sorting of the waste prior to processing; and,
- Inconsistent feedstocks and low volumes of waste.

These are all significant bottlenecks that need to be addressed for the development of battery recycling processes. CSIRO is also investigating alternative materials and resource recovery for batteries which do not contain cobalt or have low cobalt quantity with a view to ensure that the recovery process produces materials which are still high value to ensure these alternative LIB have an economic recycling process.

Research Area: The circular economy

CSIRO also has a project aimed at supporting the circular economy and reuse and recycling of commercial and industrial waste resources. ASPIRE (Advisory System for Processing, Innovation & Resource Exchange) was originally developed by CSIRO with four Melbourne municipalities. The project was led by the City of Kingston. ASPIRE is a project aimed at connecting businesses where waste or by-products from one company can be used at another. This is known as industrial symbiosis and ASPIRE has been successfully deployed in Victoria (King et al. 2016).

ASPIRE is a digital tool that also supports a social business network. It extends beyond passive waste exchange systems, where information is posted by 'sellers' online for potential 'buyers'. ASPIRE then goes one step further to create a matchmaking marketplace by actively suggesting business to business collaborations. ASPIRE has been developed in response to manufacturing companies talking to their local councils about waste disposal costs.

For more information: https://research.csiro.au/aspire

Research Area: Development of novel battery materials

CSIRO is investigating the development of new battery materials such as sulfur cathodes as well as evaluation of next generation batteries. Using the knowledge gained from these activities, CSIRO is determining the impact on recycling processes if cobalt and nickel are removed. This data will feed into the development of technical processes for battery recycling, with the goal of developing a recycling process that is flexible, and not dependent on a single LIB chemistry type and enables economic value to still be extracted. CSIRO is also developing a range of technologies which could provide valuable new manufacturing outputs for recycled products recovered from LIB, and thereby potentially providing recyclers with greater economic incentives for recycling.

References

AAS, 2017. Lithium-ion Batteries. *Australian Academy of Sciences*. Available at: http://www.nova.org.au/technology-future/lithium-ion-batteries [Accessed June 16, 2017].

ABRI, 2018. Lithium-ion Batteries. Available at: http://www.batteryrecycling.org.au/recycling/lithium-ion-batteries [Accessed March 9, 2018].

ABRI, 2017. *Promoting effective stewardship of all end of life batteries*, Melbourne: Australian Battery Recycling Initiative.

Ahmadi, L. et al., 2014. Environmental feasibility of re-use of electric vehicle batteries. *Sustainable Energy Technologies and Assessments*, 6, pp.64–74.

AMTA, 2016. *Mobile Muster 2015-2016 Annual Report*, Sydney, Australia.

AMTA, 2014. *Mobile telecommunications industry initiatives to reduce use of coltan conflict metal*, Sydney, Australia.

Aral, H. & Vecchio-Sadus, A., 2008. Toxicity of lithium to humans and the environment-A literature review. *Ecotoxicology and Environmental Safety*, 70(3), pp.349–356.

Asghar, A., 2016. *Electric Vehicle Outlook - Australia*, New York: Bloomberg New Energy Finance.

Australian Government, 2018. 2016-17 Product List. *Department of Environment and Energy*. Available at: http://www.environment.gov.au/protection/national-waste-policy/product-stewardship/legislation/product-list-2016-17 [Accessed March 7, 2018].

Australian Government, 2017a. Agreed Statement - Meeting of Environment Ministers. , (July 2017). Available at: http://www.environment.gov.au/system/files/pages/4f59b654-53aa-43df-b9d1-b21f9caa500c/files/mem6-agreed-statement.pdf [Accessed February 2, 2018].

Australian Government, 2017b. Hazardous waste permits. *Department of Environment and Energy*. Available at: http://www.environment.gov.au/protection/hazardous-waste/applying-permit [Accessed August 17, 2017].

Battery Association of Japan, 2010a. Recycling portable rechargeable batteries: protecting the limited resources. Available at: http://www.baj.or.jp/e/recycle/recycle05.html [Accessed April 19, 2017].

Battery Association of Japan, 2010b. Revised guideline for recycle marking on Li-ion batteries for the Japanese Market. Available at: http://www.baj.or.jp/e/recycle/recycle11.html [Accessed April 19, 2017].

BEA Mer, 2017. *Rapport d'enquête technique Marine investigation report*, Paris.

Benchmark Mineral Intelligence, 2016. Graphite Demand from Lithium Ion Batteries to more than Treble in 4 Years. *Benchmark Mineral Intelligence*. Available at: http://benchmarkminerals.com/graphite-demand-from-lithium-ion-batteries-to-more-than-treble-in-4-years/ [Accessed February 17, 2018].

Bhatt, A.I. & McCloskey, B., 2010. Chemistry in Australia. *Journal of Physical Chemistry Letters*, 1, pp.2193–2203.

BNEF, 2016. *Used EV batteries for stationary storage: second-life supply & costs*, New York : Bloomberg New Energy Finance

Bosecker, K., 1997. Bioleaching: metal solubilization by microorganisms. *FEMS Microbiology Reviews*, 20(3–4), pp.591–604.

Boxall, N.J. et al., 2018. Multistage leaching of metals from spent lithium ion battery waste using electrochemically generated acidic lixiviant. *Waste Management*, 74(April 2018), pp.435–445.

Brotchie, A., 2016. Li-Metal Batteries: Enter the anode matrix. *Nature Reviews Materials*, 1(4), p.16022.

Brownson, D.A.C., Kampouris, D.K. & Banks, C.E., 2011. An overview of graphene in energy production and storage applications. *Journal of Power Sources*, 196(11), pp.4873–4885.

Call2Recycle Canada, 2017. Provincial Recycling Regulations. Available at: https://www.call2recycle.ca/provincial-recycling-regulations/ [Accessed April 18, 2017].

Call2Recycle USA, 2017. Recycling Laws by State. Available at: http://www.call2recycle.org/recycling-laws-by-state/ [Accessed April 18, 2017].

Cavanagh, K., Ward, J.K., et al., 2015. *Electrical energy storage: Technology Overview and Applications*, Melbourne.

Cavanagh, K., Behrens, S., et al., 2015. *Energy storage safety: Responsible installation, use and disposal of domestic and small commercial battery systems*, Sydney, Australia.

Chen, L. et al., 2011. Process for the recovery of cobalt oxalate from spent lithium-ion batteries. *Hydrometallurgy*, 108(1–2), pp.80–86.

Chung & Sungwoo, 2011. Import and Export of Waste in Korea: Regulation and Actual Practice. In M. Kojima & E. Michida, eds. *Economic Integration and Recycling in Asia: An interium Report*. Chiba, Japan: Institute of Developing Economies Japan External Trade Organization, pp. 45–63.

CM Consulting, 2012. *Managing Canada's Waste Batteries*, Peterborough, ON.

Colmer, A.R. & Hinkle, M.E., 1947. The Role of Microorganisms in Acid Mine Drainage. *Science*, 106(2751).

Colmer, A.R., Temple, K.L. & Hinkle, M.E., 1950. An iron-oxidizing bacterium from the acid drainage of some bituminous coal mines. *Journal of bacteriology*, 59(3), pp.317–28.

Contestabile, M., Panero, S. & Scrosati, B., 2001. A laboratory-scale lithium-ion battery recycling process. *Journal of Power Sources*, 92(1), pp.65–69.

Dakota Minerals, 2017. Lithium Supply and Demand. Available at: https://www.dakotaminerals.com.au/index.php/lithium/lithium-supply-demand [Accessed April 15, 2017].

Daly, N., 2017. Australia's first battery "gigafactory" considered for Darwin. *ABC News*.

DELWP, 2015. *Managing e-waste in Victoria: Starting the conversation*, Melbourne.

Department of Energy and Environment Australia, 2016. 2016-2017 Product List for Section 108A of the Product Stewardship Act 2011. Available at: http://www.environment.gov.au/protection/national-waste-policy/product-stewardship/legislation/product-list-2016-17 [Accessed April 19, 2017].

Desjardins, J., 2017. China Leading the Charge for Lithium-Ion Megafactories. *Visual Capitalist*. Available at: http://www.visualcapitalist.com/china-leading-charge-lithium-ion-megafactories/ [Accessed March 23, 2017].

Diekmann, J. et al., 2017. Ecological Recycling of Lithium-Ion Batteries from Electric Vehicles with Focus on Mechanical Processes. *Journal of The Electrochemical Society*, 164(1), pp.A6184–A6191.

Douthwaite, M., 2015. Graphene is missing ingredient to help supercharge batteries for life on the move. *The Conversation*. Available at: https://theconversation.com/graphene-is-missing-ingredient-to-help-supercharge-batteries-for-life-on-the-move-44867 [Accessed July 16, 2017].

Dutrizac, J.E. & MacDonald, R.J.C., 1974. Ferric ion as a leaching medium. *Minerals Science and Engineering*, 6(2), pp.59–95.

European Commission, 2017. *Study on the review of the list of Critical Raw Materials. Non-critical raw materials factsheets*, Brussels: European Commission

EUWID Recycling and Waste Management, 2016. Many member states far from reaching EU Batteries Directive collection target for 2016. Available at: http://www.euwid-recycling.com/news/business/single/Artikel/many-member-states-far-from-reaching-eu-batteries-directive-collection-target-for-2016.html [Accessed July 9, 2017].

Florin, N. & Dominish, E., 2017. *Sustainability evaluation of energy storage technologies*, Sydney: UTS Institute for Sustainable Futures

Gaines, L., 2014. The future of automotive lithium-ion battery recycling: Charting a sustainable course. *Sustainable Materials and Technologies*, 1–2, pp.2–7.

Geyer, R. & Blass, V.D., 2010. The economics of cell phone reuse and recycling. *International Journal of Advanced Manufacturing Technology*, 47(5–8), pp.515–525.

Gies, E., 2015. Recycling: Lazarus batteries. *Nature*, 526(7575).

Giurco, D. et al., 2014. Circular Economy: Questions for Responsible Minerals, Additive Manufacturing and Recycling of Metals. *Resources*, 3(2), pp.432–453.

Golev, A. et al., 2016. Product flow analysis using trade statistics and consumer survey data: a case study of mobile phones in Australia. *Journal of Cleaner Production*, 133, pp.262–271.

Government of Hong Kong, 2017. 2nd Life for EV Battery. *Environment Bureau*. Available at: http://www.epd.gov.hk/epd/misc/2ndEVbattery/en/index.html [Accessed February 19, 2018].

Gratz, E. et al., 2014. A closed loop process for recycling spent lithium ion batteries. *Journal of Power Sources*, 262, pp.255–262.

Heelan, J. et al., 2016. Current and Prospective Li-Ion Battery Recycling and Recovery Processes. *Journal of Minerals, Metals and Materials Society*, 68(10), pp.2632–2638.

Hendrickson, T.P. et al., 2015. Life-cycle implications and supply chain logistics of electric vehicle battery recycling in California. *Environmental Research Letters*, 10(1), p.14011.

Humphreys, D., 2014. The mining industry and the supply of critical minerals ly. In *Critical Metals Handbook*. Oxford: John Wiley & Sons, pp. 20–40.

Hydro-Quebec, 2015. Next-Generation Batteries: Major Innovations by Hydro-Québec and CIC Energigune. Available at: http://news.hydroquebec.com/en/press-releases/781/next-generation-batteries-major-innovations-by-hydro-quebec-and-cic-energigune/ [Accessed May 5, 2017].

International Energy Agency, 2016. *Global EV Outlook 2016 Electric Vehicles Initiative*, Paris:

International Energy Agency

Jha, M.K. et al., 2013. Recovery of lithium and cobalt from waste lithium ion batteries of mobile phone. *Waste Management*, 33, pp.1890–1897.

Kaksonen, A.H., Morris, C., et al., 2014. Biohydrometallurgical iron oxidation and precipitation: Part II — Jarosite precipitate characterisation and acid recovery by conversion to hematite. *Hydrometallurgy*, 147, pp.264–272.

Kaksonen, A.H., Mudunuru, B.M. & Hackl, R., 2014. The role of microorganisms in gold processing and recovery—A review. *Hydrometallurgy*, 142, pp.70–83.

King, S. et al., 2016. Sustainable regional development through networks The case of ASPIRE (Advisory System for Processing, Innovation and Resource Efficiency) to support industrial symbiosis for SMEs. In *Seventh Regional 3R Forum in Asia and the Pacific*. Melbourne: UNCRD.

Lasker, P., Goloubeva, J. & Birtles, B., 2017. China's ban on foreign waste leaves Australian recycling industry eyeing opportunities. *ABC News*. Available at: http://www.abc.net.au/news/2017-12-10/china-ban-on-foreign-rubbish-leaves-recycling-industry-in-a-mess/9243184 [Accessed February 19, 2018].

Lewis, H., 2016. Lithium-ion battery consultation report. , pp.1–21. Available at: http://www.environment.gov.au/system/files/resources/1ac8df29-bb6c-4db6-8254-81fdba03491a/files/li-ion-battery-consultation-report.pdf [Accessed July 4, 2017].

Lewis, H., 2015. Recycling energy storage batteries. In *Clean Energy Council*. Melbourne.

Li, J. et al., 2009. A combined recovery process of metals in spent lithium-ion batteries.

Li, J., Wang, G. & Xu, Z., 2016. Environmentally-friendly oxygen-free roasting/wet magnetic separation technology for in situ recycling cobalt, lithium carbonate and graphite from spent LiCoO2/graphite lithium batteries. *Journal of Hazardous Materials*, 302, pp.97–104.

Li, L. et al., 2013. Recovery of metals from spent lithium-ion batteries with organic acids as leaching reagents and environmental assessment. *Journal of Power Sources*, 233, pp.180–189.

Li, L. et al., 2014. Recovery of valuable metals from spent lithium-ion batteries by ultrasonic-assisted leaching process. *Journal of Power Sources*, 262, pp.380–385.

Li, L. et al., 2015. Succinic acid-based leaching system: A sustainable process for recovery of valuable metals from spent Li-ion batteries. *Journal of Power Sources*.

Li, Z. et al., 2014. A review of lithium deposition in lithium-ion and lithium metal secondary batteries. *Journal of Power Sources*, 254, pp.168–182.

Lifecycles, 2017. *The potential benefits of a circular economy in South Australia*, Adelaide: Adelaide: Green Industries SA.

Liu, W.W. et al., 2016. Remanufacturing cathode from end-of-life of lithium-ion secondary batteries by Nd:YAG laser radiation. *Clean Technologies and Environmental Policy*, 18(1), pp.231–243.

Lucas, J., 2017. Galaxy Resource waves off first lithium shipment from Mt Cattlin mine. *ABC News*. Available at: http://www.abc.net.au/news/rural/rural-news/2017-01-03/galaxy-resources-waves-off-first-lithium-shipment/8159118 [Accessed February 16, 2018].

Matherson, R., 2016. Doubling battery power of consumer electronics. *MIT News*. Available at:

http://news.mit.edu/2016/lithium-metal-batteries-double-power-consumer-electronics-0817 [Accessed February 23, 2017].

Meshram, P., Pandey, B.D. & Mankhand, T.R., 2015. Hydrometallurgical processing of spent lithium ion batteries (LIBs) in the presence of a reducing agent with emphasis on kinetics of leaching. *Chemical Engineering Journal*.

Metalary, 2017. Lithium Price. Available at: https://www.metalary.com/lithium-price/ [Accessed April 4, 2017].

Mishra, D. et al., 2008. Bioleaching of metals from spent lithium ion secondary batteries using Acidithiobacillus ferrooxidans. *Waste Management*, 28, pp.333–338.

Mitsubishi Motors, 2013. Mitsubishi 2012 i-MiEV Dismantling Guide. , (June). Available at: http://elvsolutions.org/wp-content/uploads/2013/06/2012_I_Dismantling_guide.pdf [Accessed November 18, 2017].

MobileMuster, 2013. *Mobile Australia - a report into how we use and recycle our mobiles*, Sydney, Australia.

Mohr, S.H., Mudd, G. & Giurco, D., 2012. Lithium Resources and Production: Critical Assessment and Global Projections. *Minerals*, 2(4), pp.65–84.

Neometals, 2018. Neometals. Available at: http://www.neometals.com.au/ [Accessed March 9, 2017].

Niu, Z. et al., 2014. Process controls for improving bioleaching performance of both Li and Co from spent lithium ion batteries at high pulp density and its thermodynamics and kinetics exploration. *Chemosphere*, 109, pp.92–98.

NSW EPA, 2017. Innovation in Priority Problem Waste Management Grants Program. Available at: http://www.epa.nsw.gov.au/wastegrants/priority-problem-wastes.htm [Accessed April 19, 2017].

O'Farrell, K., Veit, R. & Vard, D.A., 2014. *Study into market share and stocks and flows of handheld batteries in Australia*, Melbourne.

Pagnanelli, F. et al., 2016. Cobalt products from real waste fractions of end of life lithium ion batteries. *Waste Management*, 51, pp.214–221.

Park, J. & Ha, S., 2014. Understanding consumer recycling behavior: combining the theory of planned behavior and norm activation model. *Family and Consumer Sciences*, 42, pp.278–291.

PF Metals, 2017. PF Metals to recycle Batteries in Australia. Available at: http://www.batteryrecycling.org.au/pf-metals-to-recycle-batteries-in-australia [Accessed March 23, 2017].

QNovo, 2017. Inside the battery of a Nissan Leaf. *ONovo Incorporated*. Available at: https://qnovo.com/inside-the-battery-of-a-nissan-leaf/ [Accessed June 20, 2017].

Queensland Government, 2017. Queensland Electric Super Highway. Available at: https://www.qld.gov.au/transport/projects/electricvehicles/super-highway [Accessed March 9, 2018].

Randell, P., 2016. *Waste lithium-ion battery projections*, Woodend.

Randell, P., Pickin, J. & Grant, B., 2014. *Waste generation and resource recovery in Australia - reporting period 2010/11* Blue Environment Pty Ltd, ed., Canberra: Department of

Sustainability, Environment, Water, Population and Communities and Blue Environment Pty Ltd.

Randell, P., Pickin, J. & Latimer, G., 2015. *Hazardous-Waste-Infrastructure-Needs-Capacity-Assessment*, Canberra.

Rawlings, D.E., 2002. Heavy Metal Mining using Microbes 1. *Annu. Rev. Microbiol*, 56, pp.65–91.

Rawlings, D.E., Dew, D. & Du Plessis, C., 2003. Biomineralization of metal-containing ores and concentrates. *Trends in Biotechnology*, 21(1), pp.38–44.

Read, R., 2015. Australia Mobile Decade - 10 years of Consumer Insights into Mobile Use and Recycling 2005-2015. *Mobile Muster*, pp.1–68. Available at: https://www.mobilemuster.com.au/media/107666/australia_s_mobile_decade.pdf [Accessed April 3, 2018].

Recycling International, 2013. EU battery collection targets “too ambitious”? *Recycling International*.

Renault, 2017. Renault and Powervault Give EV Batteries a “second-life” in Smart Energy Deal. *Renault*. Available at: http://media.renault.com/global/en-gb/renaultgroup/media/pressrelease.aspx?mediaid=92203 [Accessed June 5, 2017].

Samsung, 2018. 8-Point Battery Safety Check. *Samsung*. Available at: http://www.samsung.com/au/galaxynote7-information/ [Accessed March 1, 2018].

Sarath, P. et al., 2015. Mobile phone waste management and recycling: Views and trends. *Waste Management*, 46, pp.536–545.

Skirrow, R.G. et al., 2013. *Critical commodities for a high-tech world: Australia’s potential to supply global demand*, Canberra.

SolidEnergy, 2018. Hermes™. *SolidEnergy*. Available at: http://www.solidenergysystems.com/hermes/ [Accessed March 26, 2018].

Swain, B., 2017. Recovery and recycling of lithium: A review. *Separation and Purification Technology*, 172(August), pp.388–403.

U.S. Geological Survey, 2015. *Lithium - Minerals Commodity Summaries*,

Vaughan, A., 2017. Nissan launches British-made home battery to rival Tesla’s Powerwall. *The Guardian*. Available at: https://www.theguardian.com/business/2017/may/04/nissan-launches-british-made-home-battery-to-rival-teslas-powerwall [Accessed May 4, 2017].

Vikström, H., Davidsson, S. & Höök, M., 2013. Lithium availability and future production outlooks. *Applied Energy*, 110, pp.252–266.

WA Waste Authority, 2017. Household Hazardous Wastes. Available at: http://www.wasteauthority.wa.gov.au/programs/funded-programs/household-hazardous-waste/#0 [Accessed April 19, 2017].

WA Waste Authority, 2014. WA Transitional E-Waste Program (Archived Program). Available at: http://www.wasteauthority.wa.gov.au/programs/funded-programs/archived-programs [Accessed April 19, 2017].

Wang, J. et al., 2011. Active lithium replenishment to extend the life of a cell employing carbon and iron phosphate electrodes. *Journal of Power Sources*, 196(14), pp.5966–5969.

Wang, X., Gaustad, G., Babbitt, C.W., et al., 2014. Economic and environmental characterization of an evolving Li-ion battery waste stream. *Journal of Environmental Management*, 135, pp.126–

134.

Wang, X., Gaustad, G., Babbitt, C.W., et al., 2014. Economies of scale for future lithium-ion battery recycling infrastructure. *Resources, Conservation and Recycling*, 83, pp.53–62.

Wanger, T.C., 2011. The Lithium future-resources, recycling, and the environment. *Conservation Letters*, 4(3), pp.202–206.

Warnken Industrial and Social Ecology Pty Ltd, 2010. *Analysis of Battery Consumption, Recycling and Disposal in Australia*, Sydney, Australia.

Williams, W. & Lewis, D., 2005. Convergent interviewing: a tool for strategic investigation. *Strategic Change*, 14(4), pp.219–229.

Wills, R., Buckley, H. & Prentice, N., 2018. *A lithium industry in Australia*, Perth: : Future Smart Strategies.

Xu, J. et al., 2008. A review of processes and technologies for the recycling of lithium-ion secondary batteries. *Journal of Power Sources*, 177(2), pp.512–527.

Zeng, G. et al., 2012. A copper-catalyzed bioleaching process for enhancement of cobalt dissolution from spent lithium-ion batteries. *Journal of Hazardous Materials*, 199, pp.164–169.

Zeng, X. & Li, J., 2014. Spent rechargeable lithium batteries in e-waste: Composition and its implications. *Frontiers of Environmental Science and Engineering*, 8(5), pp.792–796.

Zeng, X., Li, J. & Liu, L., 2015. Solving spent lithium-ion battery problems in China: Opportunities and challenges. *Renewable and Sustainable Energy Reviews*, 52, pp.1759–1767.

Zeng, X., Li, J. & Shen, B., 2015. Novel approach to recover cobalt and lithium from spent lithium-ion battery using oxalic acid. *Journal of Hazardous Materials*, 295, pp.112–118.

Zeng, X., Li, J. & Singh, N., 2014. Recycling of spent lithium-ion battery: A critical review. *Critical Reviews in Environmental Science and Technology*, 44(10), pp.1129–1165.

Zero Waste SA, 2017. E-waste Recycling: Your Questions Answered. Available at: http://www.zerowaste.sa.gov.au/e-waste/e-waste-recycling-your-questions-answered [Accessed March 23, 2017].

Zhang, P. et al., 1998. Hydrometallurgical process for recovery of metal values from spent lithium-ion secondary batteries. *Hydrometallurgy*, 47(2–3), pp.259–271.

Zhang, W. et al., 2017. Preparing graphene from anode graphite of spent lithium-ion batteries. *Frontiers of Environmental Science and Engineering*, 11(5), pp.1–8.

Zhu, S.G. et al., 2012. Recovery of Co and Li from spent lithium-ion batteries by combination method of acid leaching and chemical precipitation. *Transactions of Nonferrous Metals Society of China (English Edition)*, 22(9), pp.2274–2281.

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