FUTURE BATTERY INDUSTRIES CRC

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Australian landscape for lithium-ion battery recycling and reuse in 2020

CURRENT STATUS, GAP ANALYSIS AND INDUSTRY PERSPECTIVES

Produced for the Future Battery Industries CRC

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Australia's National
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Executive summary

Battery usage is growing globally driven by increasing electrification of transport and renewables energy generation storage sectors. In this regard, Australia is no exception and battery usage is increasing across all sectors. Although beneficial for emissions reduction, this growth is leading to an emerging problem of end of life waste management. In addition to the environmental and safety concerns, the value associated with valuable battery metals and materials used in LIBs is lost from Australian economy. This lost value could be between AUD 4,400 and 17,200/tonne of battery translating to $603 million to $3.1 billion due to the poor LIB collection rates, offshore recycling and landfilling of the LIB battery waste.

This report discusses the battery growth drivers and markets and the status of the Australian recycling industry. A comprehensive gap analysis and literature review was undertaken to identify key issues and challenges the incumbent battery recycling industry faces. Crucially, a stakeholder survey across all sectors of the battery value chain was undertaken to identify key barriers and challenges the industry faces. Overall, all stakeholder sectors believe there are strong opportunities for future Australian industries, namely second-life, recycling and materials recovery and cell manufacturing as the top opportunities identified.

Through in-depth analysis of the current policy landscape, stakeholders identified the following opportunities to strengthen and grow Australia's domestic recycling capability and generate new industries and employment opportunities:

International policy area

1. Improved labelling and barcoding or QR coding requirements for battery cells. An opportunity presents itself for Australia to take a global leadership position in coordinating agreement between international Governments of major manufacturing regions and markets of China, Japan, United States of America and European Union.
2. Guidelines to ensure battery manufacturers and users make available State of Health information for end-of-life batteries. Similar to above an opportunity exists to either influence the current changes to the European Union battery regulations or to setup International Product Stewardship schemes through coordination of major international governments.

National policy and regulation area

1. Exploring a National Product Stewardship for all batteries and assistance for State Governments to establish recycling in each State.
2. Investigating a unified National battery and battery waste transportation policy between Federal, State and Territory Governments and Industry. Industry participants in this report noted that the current transportation policy hinders the recycling industry.
3. Stakeholders identified lack of enforcement of policy as a big business barrier as it gives advantages to unethical processors that are less costly but less effective at achieving good outcomes. There is a clear opportunity here to increase the rate of enforcement to remove

these unethical business practices and ensure waste is correctly recovered and recycled in a safe manner.

4. Due to the lack of information and understanding both in Australia and globally, there is a clear opportunity to increase research in this area and coordination of State and Territory governments, EPAs and emergency response agencies to provide increased safety to the general population and first responders when dealing with battery fires.
5. Investigation of a National public education campaign with a unified and clear message for battery recycling. There is an opportunity here for a joint State and Territory Government and Industry led scheme to promote consumer awareness of battery (and other e-waste) recycling.
6. A comprehensive review of policies, regulations and guidelines for end-of-life battery waste management. Industry bodies such as ABRI have some guidelines available for public utilisation, however there is an opportunity to improve/extend these guidelines by Governments and Industry working together to identify key challenges that require new policy and/or guideline changes.
7. Exploration of a Federal level strategy and master plan for the next 25+ years to build long term economic prosperity and value
    a. Investigate regulations regarding keeping waste on-shore
    b. Investigate associated economic and environmental impacts
    c. Identify role of regulatory changes vs. industry led changes needed.
8. Policies and regulations to assist growth of second-life battery remanufacture industry.

Industry development area

1. Increasing consumer collection facilities and improving locations to provide greater convenience to boost collection rates.
2. Development of new markets for recycled and recovered products and investment in infrastructure and markets for using the materials.

Research area

1. Provide research and solutions for battery fire safety risks during collection, transportation and storage including development of solutions to deal with broken, damaged, overcharged or overheated LIBs.
2. Provide technology advancement, technology support for battery value chain in Australia not only in mining and primary material processing, but also downstream in the battery manufacturing, maintenance, and end-of-life treatment.
3. Research on developing end markets for the recovered battery materials for use in alternative industries. Identification of barriers, technical challenges and opportunities.
4. Develop new economically feasible recycling technologies for low cobalt chemistry batteries.
5. Promote life cycle assessment benefits of recycling and reduced value chain emissions from downstream processing in Australia.

6. Provide technology development and support to improve materials recycling efficiency and improve costs to help business economic viability.

Acknowledgments

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Part I Why is lithium-ion battery waste an emerging problem?

The driving force and rationale for battery recycling

1.1 Introduction

Globally, in the effort to combat rising CO_2 emissions from the transportation and electricity generation sectors, battery usage is growing. Australia is no exception to this global trend with high levels of grid connected batteries and growth in electric vehicles predicted for the near-term future. This increasing deployment of batteries will eventually result in significant quantities of waste batteries when these devices reach end-of-life. Battery waste is generally toxic and harmful to human health and the environment if not managed properly. The predicted demands for critical metals required to build new lithium-ion batteries (LIBs) combined with the current process of landfill disposal, raise environmental and financial concerns where waste batteries with concentrated valuable battery elements are disposed without effective materials recovery. However, through development of an effective recycling and resource recovery infrastructure, Australia has an opportunity to improve energy security and waste and resource security. This report discusses the battery markets and waste management strategies used in Australia and presents an understanding of the current (2020) landscape for battery recycling, with a focus on the emerging LIB waste stream.

1.2 Transition to renewable energy requires deployment of LIBs

According to the World Resource Institute [1], the energy sector contributed to 72% of the global human made greenhouse gas emissions (where transportation contributes 15%). It is widely recognised that a global transition to low carbon technologies is required to mitigate the effects of climate change and loss of valuable resources. This can be achieved through transition from the current Linear Economy (Make-Use-Dispose) to a Circular Economy (Make-Use-Reuse-Recycle) to reduce primary resource utilisation through materials recovery for remanufacture technologies [2]. The global energy demands are estimated to grow by 30% by 2040 and most of the growth will be met by renewable energy sources [3]. Over the past few decades, the price reductions in renewables generation has meant that it is now cost competitive (or better in some instances) with traditional fossil fuels in the Energy Sector. Existing fossil fuel generation assets in Australia typically have design life-times of 50 years with an actual operational life-time, on average, of 33 years [4]. At the end of their lifetime, these traditional power plants are gradually being replaced by technology harnessing energy from renewable sources such as solar, wind and hydro as Australian States and Territories, and more broadly global jurisdictions, look to achieve their planned emissions reduction targets. In Australia, renewables are expected to account for two-thirds of investment in power plants by 2040 to replace existing coal generation assets [5]. Due to the intermittent nature of renewable energy generation, efficient and sustainable energy storage solutions are needed which creates significant demand for batteries, in particular, LIBs and for certain applications also lead acid batteries (LABs).

1.3 Growing EV adoption will generate a significant amount of end-of-life LIBs

Since 2010, many Governments around the world have introduced legislation to promote electric vehicles (EVs) with the aim to phase out internal combustion engines within the next few decades. Figure 1 shows the EV uptake over the past decade. The global EV market grew at 40-70% each year since 2011, with more than 2.1 million new electric cars sold in 2019 [6]. In 2014 the global battery market size was US$ 62 billion [7] and almost doubled to US$ 108 billion in 2019 [8]. Bloomberg forecasts that this rising trend will continue and annual global electric vehicle sales will reach 24.4 million EVs by 2030 (Figure 2) [9]. Likewise, the global battery consumption is expected to increase five fold in the next ten years and is expected to grow by 25% annually to 2.600GWh in 2030 [10].

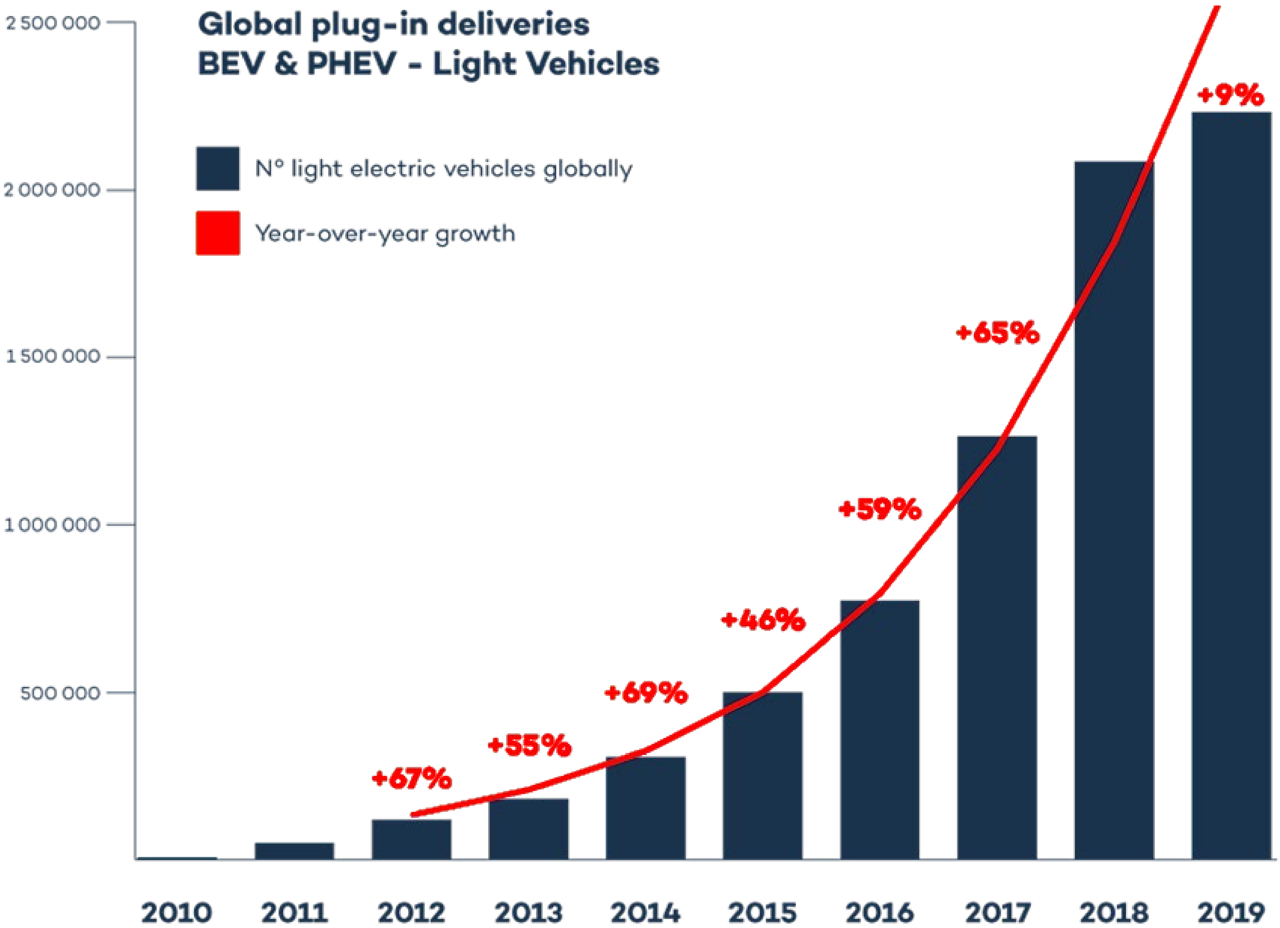


Figure 1 Global EV sale trend between 2010 and 2019 [6].

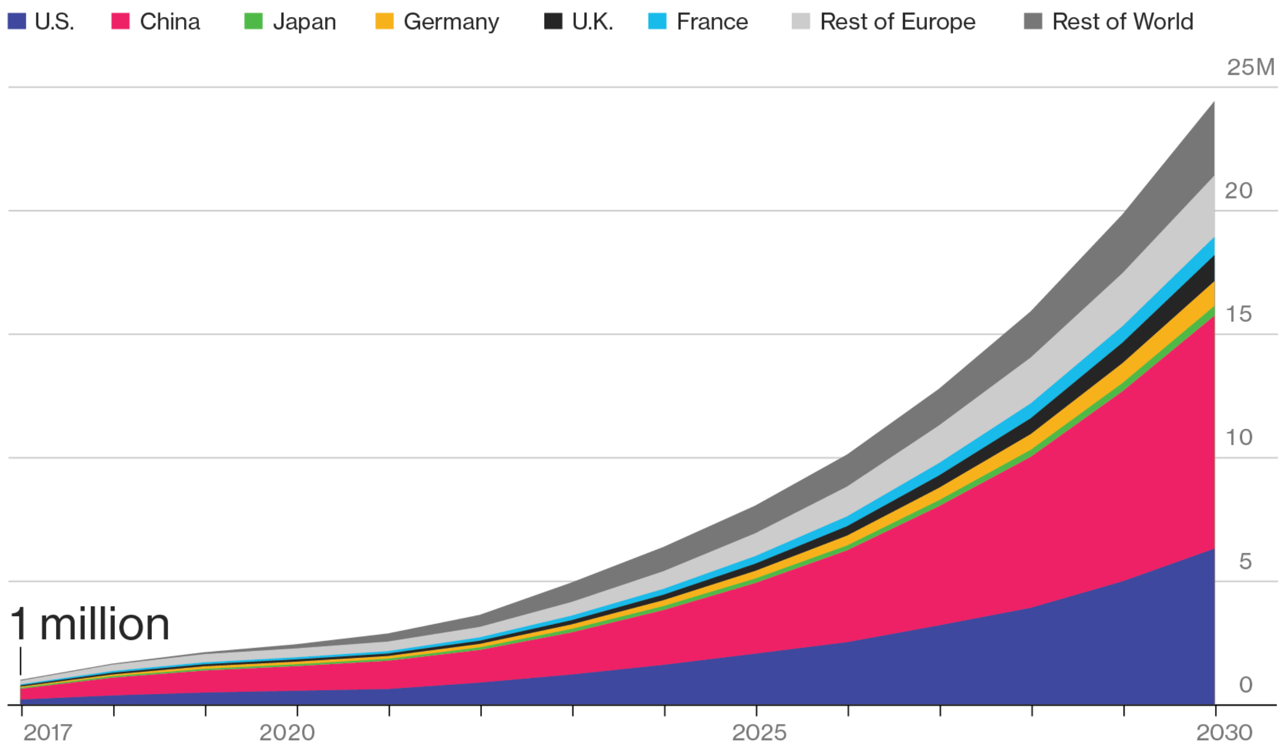


Figure 2 Global EV uptake in major countries [9].

The rapid growth in EVs lead to tremendous demand for LIBs. Given LIBs generally have a life span of 5-10 years [11] (though current development trends are pushing towards 10-15 years), and the widespread electrification in renewable energy storage system (ESS) and EV adoption, it is reasonable to expect significant volumes of spent and end-of-life batteries in the near-term future. Concomitantly, a growth in demand for battery and strategic metals will be needed to meet the requirements for continuous growth in battery production.

1.4 HSE risks and valuable metal resource in waste LIBs

Depending on the type of battery, waste streams may consist of various heavy metals and toxic compounds, including hazardous metals such as mercury (Hg), lead (Pd), nickel (Ni), cadmium (Cd). The most common battery types being recycled currently are lead acid (LAB), nickel metal hydride (NiMH) and alkaline batteries due to the high toxicity of materials and/or volume available. LAB recycling is a prime example for an effective and economically feasible battery recycling process. However, the recycling methodology is not compatible for recovery of materials from LIBs and hence LIB specific technology will need to be deployed for LIB recycling. There are some synergies developing in the collection networks, drop-off points and infrastructure for LIBs with the other common battery types such as LABs. This synergy can help increase the waste collection rates of LIBs if further developed and expanded.

Similar to other battery waste types, the commonly used materials in LIBs are problematic from an environmental and safety perspective. LIBs typically employ the hexafluorophosphate salt, $LiPF_6$ (most common electrolyte salt used at present) which is problematic since it causes systemic toxicity, respiratory failure, cardiac arrest and death even with little physical contact with the compound [12]. $LiPF_6$ also reacts very easily with mucous tissues and is highly reactive with water to release dangerous hydrogen fluoride gas (HF) [13]. In addition, the electrolyte medium used to dissolve $LIPF_6$ is not water based (as in LABs) but consists of flammable and toxic alkylcarbonate solvents which not only pose an environmental risk but a potential fire and explosion risk, under certain conditions, if incorrectly disposed. Aside from the risks of a battery fire, if LIBs are disposed of in general landfill, the fire and environmental risks are magnified due to the mixed nature of the waste. For example, a single battery fire can easily and rapidly propagate in landfill sites when surrounded by other flammable materials which can increase the fire size and associated pollution. There have been a number of fires associated with LIBs in recycling facilities and landfill sites reported. Within Australia (and internationally) the recycling industry is evolving rapidly to address key risks such as fires and environmental damage. However, there is an opportunity for more in-depth and rapid research around fire safety and environmental management which is required to support the industry.

Furthermore, LIBs contain concentrated metals, such as cobalt, nickel, manganese, aluminium, and copper. Among these metals, cobalt and nickel are toxic heavy metals. Cobalt ions, such as Co^{2+}, are toxic to humans and aquatic life [14]. If landfilled, the metal ions in batteries can readily leak from damaged casings of buried batteries and hence contaminate soil and ground water. As significant growing numbers of LIBs reach the end of their usable life, waste management will become a big issue if landfill disposal continues.

Driven by growth of the electric vehicle industry, the quantity and weight of spent LIBs globally in 2020 will surpass 25 billion units and 500 thousand tons[1], respectively [15]. Given the realistically anticipated volumes and the associated content of concentrated metals, the spent LIBs represent a considerable asset in terms of the monetary value of their metal content. The current price of metals commonly present in LIBs are listed in Table 1.

It is pertinent to point out that discussions and reports around lithium recovery (or recycling) in the majority of cases refer to lithium in the form of lithium carbonate and/or lithium hydroxide. These materials have to be converted in a subsequent difficult and risky process into high purity electrolyte grade $LiPF_{6,}$ (most common and widely used electrolyte salt in LIBs). Among the LIB components, $LiPF_6$ is a highly valuable compound. The $LiPF_6$ value in 2016 was US$ 14,600 per ton rising to US$ 20,000 to 35,000 per ton in 2020 and hence has a high recoverable resource value, similar to Co and Ni (US$ 32,000 and 17,500, respectively) [16].

[1] Depending on reference source the terms ton and tonne are both used throughout this document. For clarity, 1 ton is equal to 907.185 kg and 1 tonne is equal to 1000 kg

Table 1 Component range of typical LIBs and current commodity value of each metal element in 2020.

Component	Commodity Value[a] US$/ton	Commodity Value[a] US$/ton
	Jan 2020	**Feb 2021**
Cobalt	37,250	41,250
Nickel	14,193	17,647
Lithium	49,500	62,500
Lithium hexafluorophosphate		55,000 - 100,000 [b]
Manganese	32	31
Iron (ore)	93	158
Aluminium	1,804	1,961
Copper	5,620	7,000

a: https://tradingeconomics.com/commodities, accessed on 2nd February 2021. Note the prices are highly volatile and fluctuate depending on market and trading factors and may change at the time of reading this report. b: data obtained from web resources of commercial suppliers as well as the DOE (US).

Part II Battery market trends and future battery waste matrix

Global market trends and Australian status

2.1 Introduction to batteries

Commercially available batteries utilise a range of different chemical reactions for energy storage. Each of these battery chemistries requires dedicated recycling processes, which are not mutually compatible for mixed battery chemistry waste processing. The current market share of different types of batteries and future market trends determine how the battery waste materials will be processed now and into the future.

Batteries are electrical energy storage devices which convert chemical energy into electrical energy. All battery devices have similar construction principles, namely electrodes for the energy storage and an electrolyte to carry the charge between electrodes. Many large batteries sold currently, referred to as battery packs, are comprised of smaller battery cells. In the case of LIB battery packs, these cells typically are in coin or button cell, cylindrical or pouch cell geometries.

Each battery cell is composed of three main components: a positive electrode (cathode), a negative electrode (anode), and an electrolyte. The electrodes are where the chemical reactions, oxidation and reduction, occur. While the electrolyte allows for the transfer of charge through ion mobility between the electrodes. Other components are the separator, which prevents physical contact (short circuiting) between electrodes, the casing, which encapsulates the battery and any safety features a battery might have, and notably an electronic battery management system in battery packs.

As for lithium-ion battery, the term LIB covers a wide range of different technology types. A typical LIB structure and composition are shown in Figure 3 and Figure 4. Some examples of popular LIBs cathode, anode and electrolyte choices are shown in Table 2.

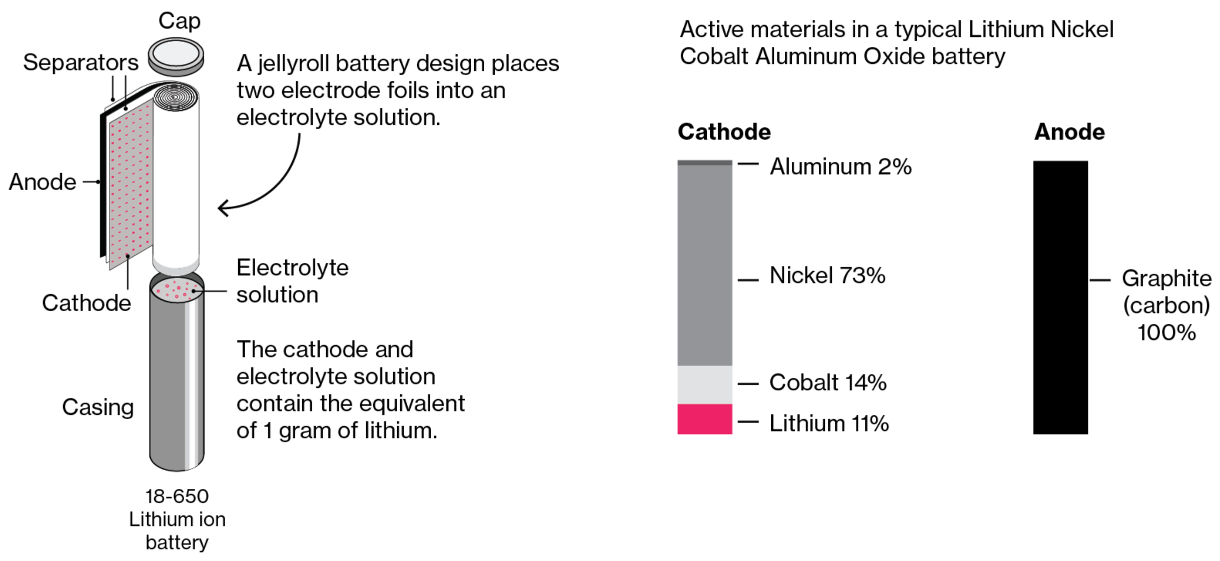


Figure 3 A typical lithium-ion battery structure and elemental composition [17].

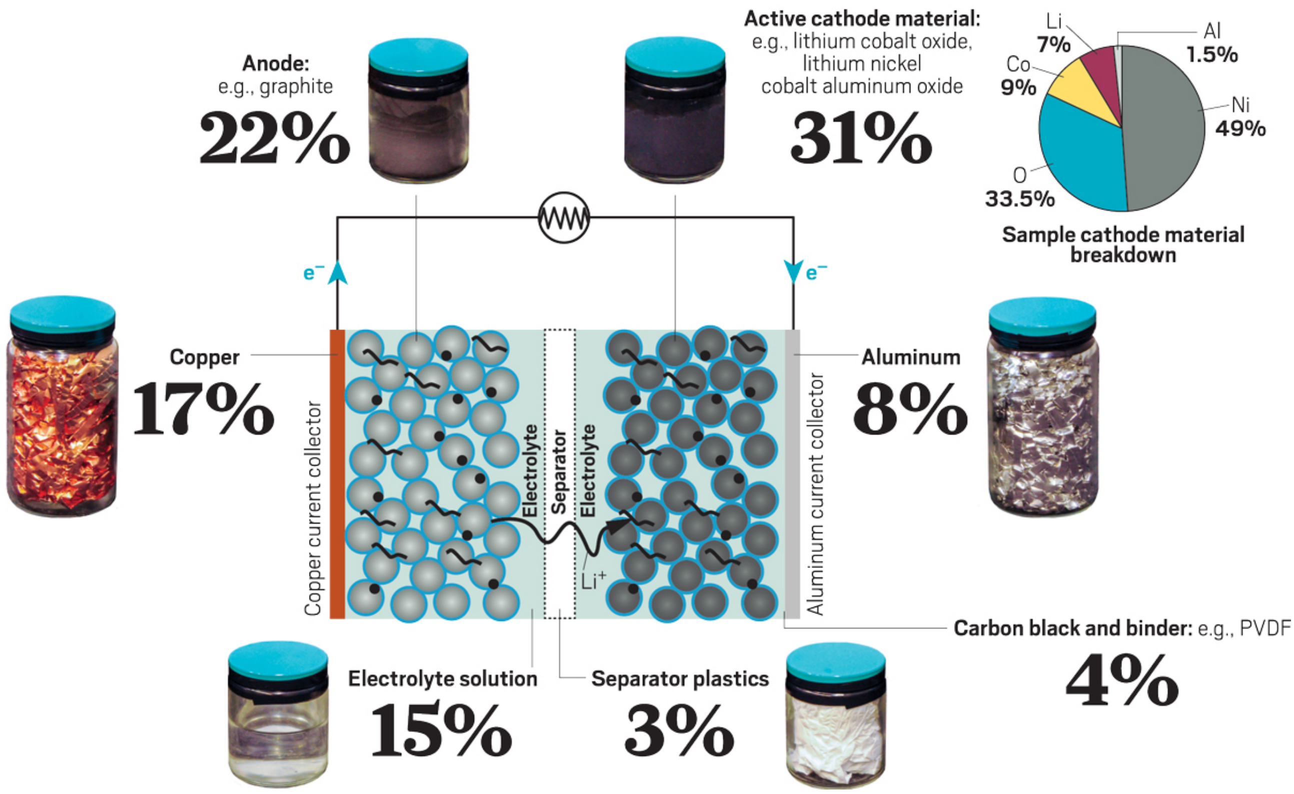


Figure 4 Material composition of a typical lithium-ion battery [18].

Table 2 Summary of the popular lithium-ion battery technologies cathode, anode and electrolyte types.

Positive Electrode	Negative Electrode	Electrolyte
Nickel-Manganese-Cobalt oxide (NMC)	Graphite (includes graphene)	Liquid electrolyte (typically carbonate solvents with a Li salt)
Nickel-Cobalt-Aluminium oxide (NCA)	Lithium titanate (LTO)	Lithium-ion conducting polymer (LiPo)
Cobalt oxide (LCO)	Hard carbon	Lithium-ion conducting inorganic solid (solid state)
Lithium-iron-phosphate (LFP)	Tin-Cobalt alloy	
Lithium-Manganese oxide (LMO)	Silicon-Carbon	
Sulfur	Lithium Metal	

2.2 Global battery market breakdown by type and chemistry

Due to the requirements for different applications in terms of power, energy storage capacity and storage time, no single battery chemistry or type can accommodate all application types. Many different types of batteries have been developed and configured for these varying applications. Batteries can be grouped into primary and secondary batteries, where primary batteries are non-chargeable, secondary batteries which are rechargeable. Batteries are also classified according to their application type, such as consumer and portable electronics, stationary storage, automotive, starter lighting and ignition, deep discharge etc. It is more common, for the general public to classify batteries by chemistry type, which includes LABs, nickel-based batteries, lithium-based batteries, alkaline batteries, and mercury batteries, where LABs and LIBs are dominant on global battery market with market share of 49.9% and 45.7% in 2019 [19], respectively as shown in Figure 5. LIBs alone are projected to reach a value of US$ 53.8 billion by 2024, with a compound annual growth rate (CAGR) of 11% between 2019 and 2024 [20]. It is expected that 81.8% of rechargeable battery market growth between 2019 and 2024 will come from LIBs [19].

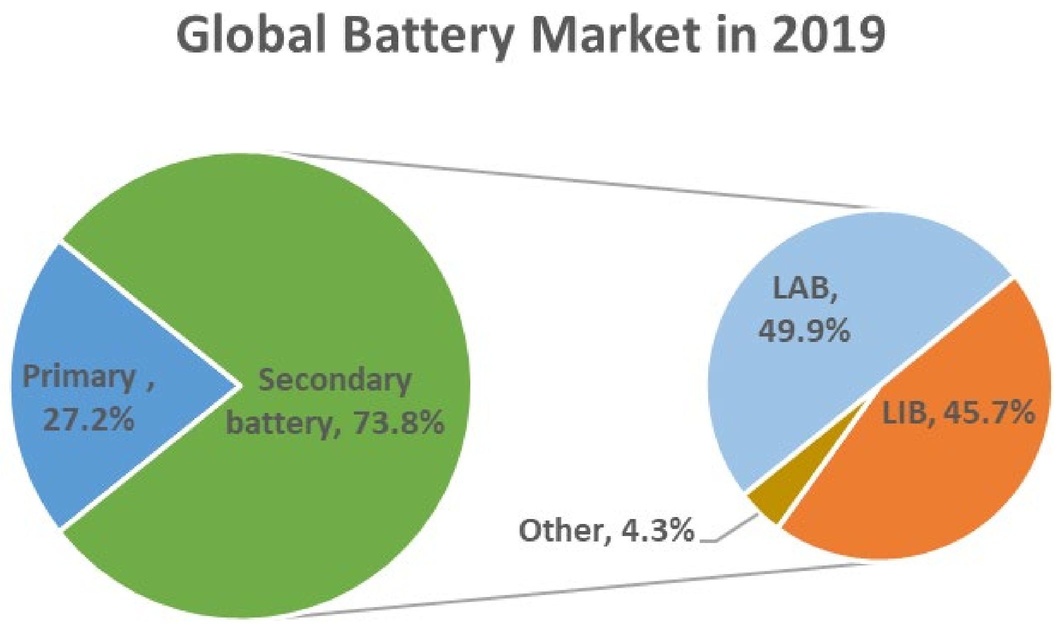


Figure 5 Global battery market share by different type of batteries in 2019. Data derived from reference [19].

2.3 LIBs will take over LABs to be the dominant battery type

2.3.1 Comparison of LIBs and LABs attributes, application, and growth trends

LABs are a mature technology and have been well established and widely adopted for over a century. Comparatively, LIBs are a newer technology commercialised in the 1990s compared to LABs invented in 1859. LABs has a very low energy-to-weight and energy-to-volume ratio. LIBs has numerous advantages over LABs, such as high energy density, high specific energy, high voltage capacity, long cycle life, and lower self-discharge rate which make LIBs the battery chemistry of choice for EV and portable device applications. In comparison, the weight and size taken up by LABs for the same amount of stored energy are much larger.

The major application for LABs is automotive batteries for starting, lighting, and ignition (SLI) which accounts for 75% of the total LABs utilisation, the rest being traction batteries/stationary batteries used for standby and emergency power supply [21]. LABs ability to supply high surge currents along with the low cost make it still attractive for use in most backup power solutions in traditional industrial applications. Having the biggest market share, LABs are expected to continue growing in the future but at a much slower rate compared to LIBs. It is predicted, that driven by high demands from the ESS and EV sectors, LIB production will surge in the future.

2.3.2 LABs a successful recycling story but recycling technology not transferable

Despite LABs containing toxic lead, they have the largest market share which inevitably leads to a larger waste volume. Globally in some jurisdictions, lead acid recycling is legislated by Governments hence the high collection and recycling rate (95-99% achieved in most developed regions, about 80% achieved in some of the developing regions) [22]. The recycling and reuse of LABs is, thus far, the most successful ecosystem in battery waste management. LAB recycling technology, due to differences in materials, is not utilisable in LIB recycling. However, there are opportunities within Australia for the existing collection network to be expanded to encompass LIBs. This not only addresses the current issue of low LIBs collection rates, but also concomitantly enables the existing collection and transport industry sector to expand.

Large size batteries will dominant in the future battery waste stream.

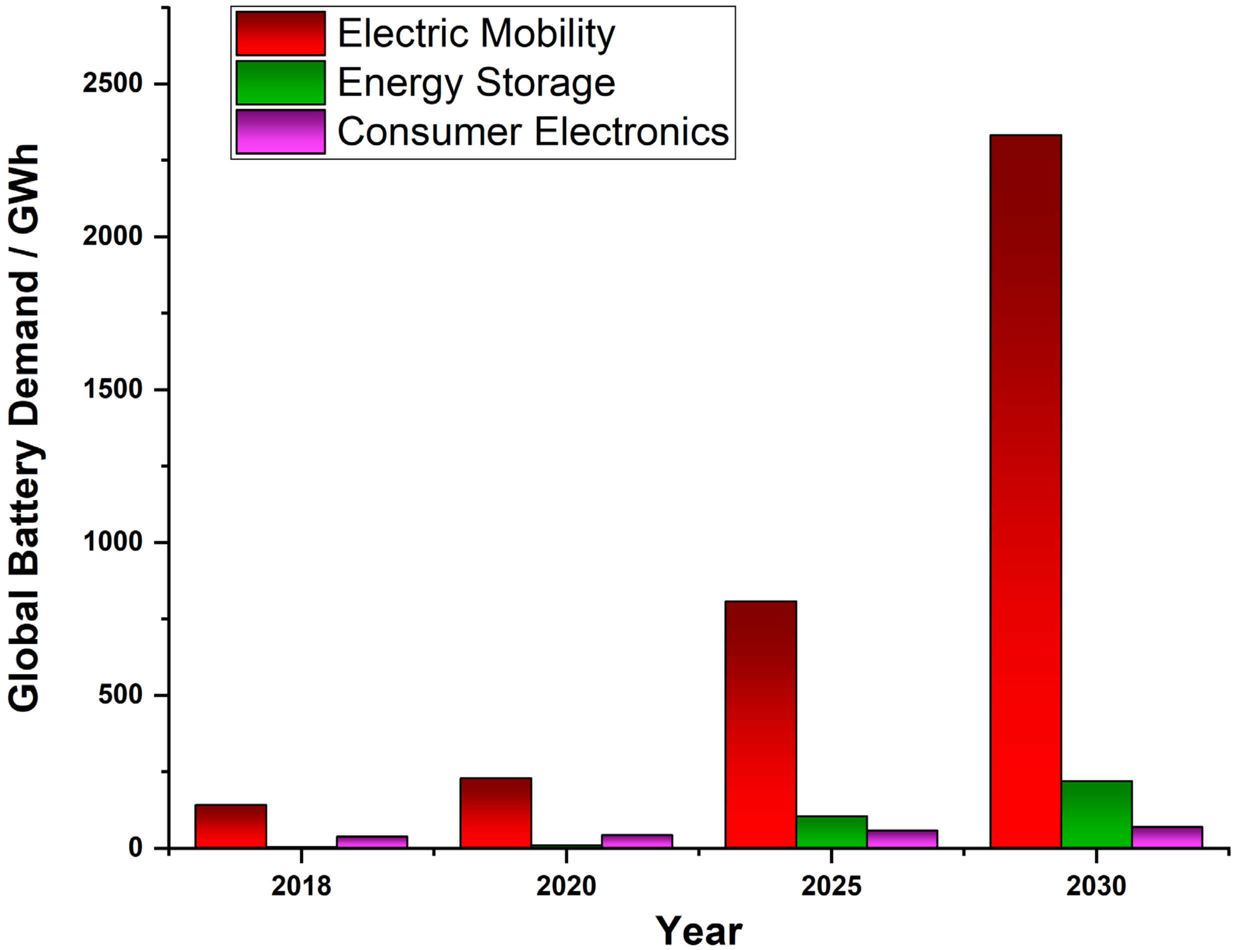


Figure 6 Global battery demand by application from 2018 to 2030 (reproduced from data in reference [10]).

Figure 6 illustrates that batteries for electric mobility are expected to have the largest growth rate and significant high demand in the next ten years, followed by energy storage batteries. The future landscape of battery waste will be very different from today where large battery packs, due to EVs and ESS will be dominant in battery waste streams. For LIBs, battery packs are constructed from numerous small individual cells (cylindrical or prismatic formats dependent on manufacturer). Figure 7 illustrates how small cylindrical LIB cells pack into a large car battery pack and a visual comparison of the size of LIBs used in mobile phones, tablets and EVs is illustrated in Figure 8.

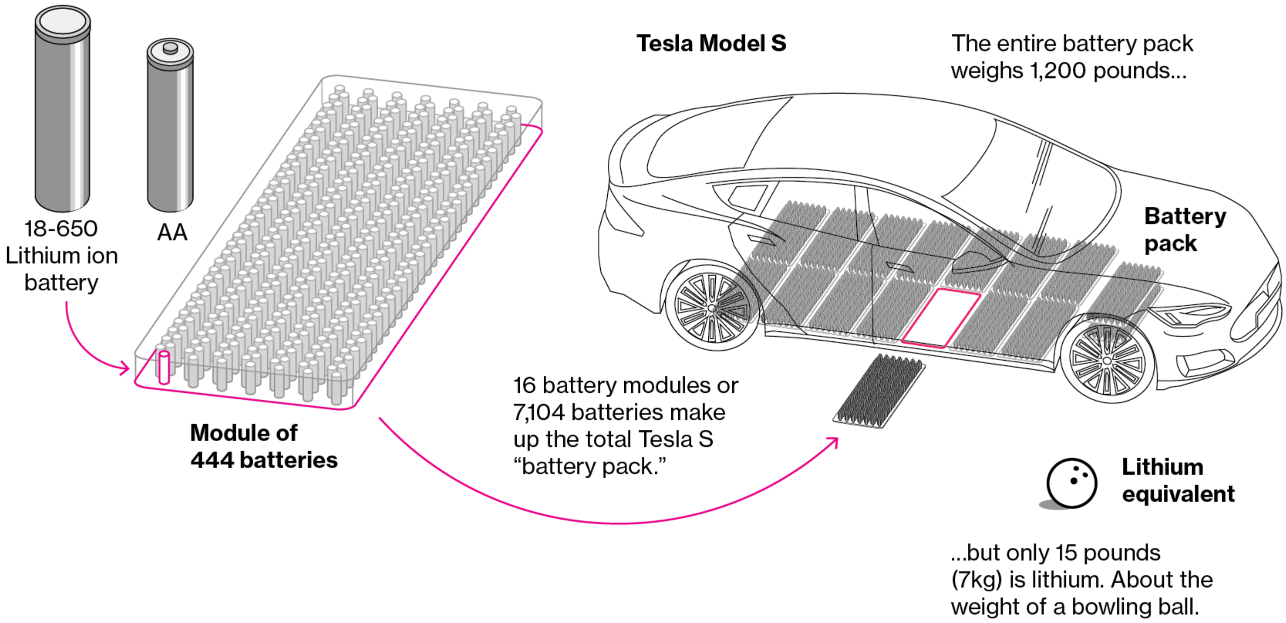


Figure 7 Schematic of a Tesla EV battery pack design from cells, modules and system [17].

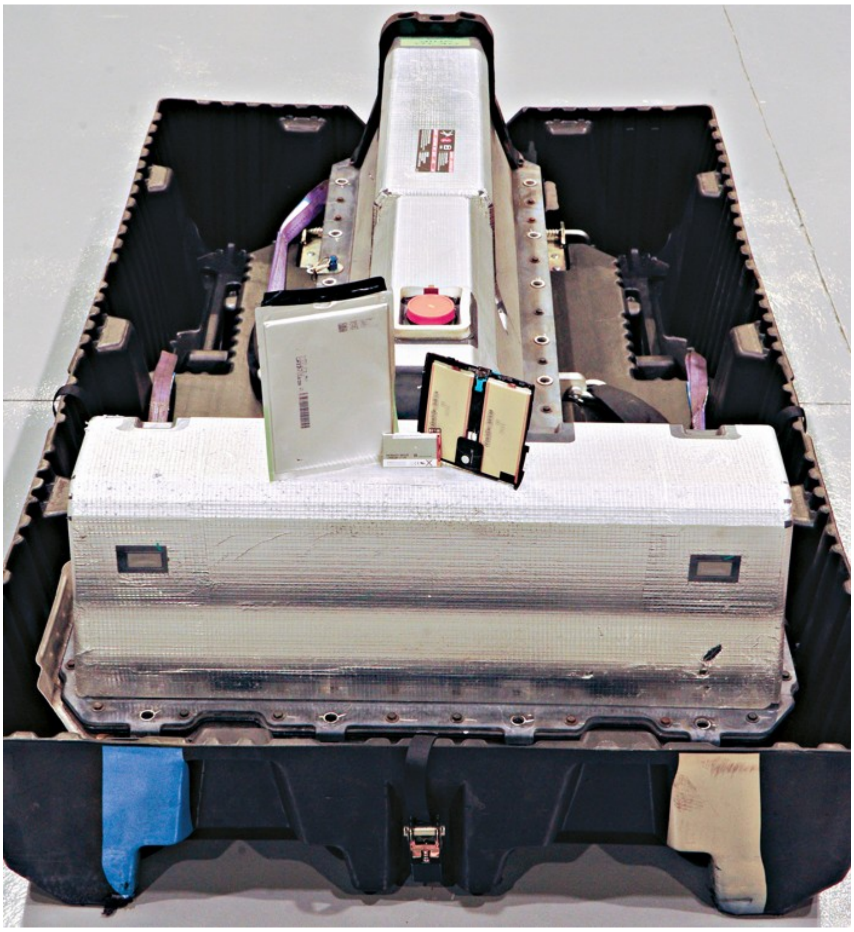


Figure 8 Comparison of Chevy volt battery pack (T shaped system), individual cell (left) and for comparison, mobile phone battery (centre) and iPad battery right. 288 cells are utilised to construct the full battery pack [18].

2.4 ESS, EV and battery waste status and trend in Australia

2.4.1 Landscape of battery usage for renewable energy storage

According to Geoscience Australia, the Australian continent has the highest solar radiation per square metre of any continent and consequently some of the best solar energy resource in the world. Consequently, Australia is one the best places to utilise renewable energy. In Australia, 4.8 million tonnes of CO_2-e was generated in 2018-2019 from the electricity sector alone to meet the current usage of over 200 TWh per annum (where 1 TWh = 1000 GWh) [23]. In Australia, over 70% of electricity generated is derived from emissions-intensive fossil fuels (56% coal and 21% gas in 2019) [24]. Due to the nation's heavy reliance on fossil fuels in the production of electricity, Australia has one of the highest levels of CO_2 emissions per capita globally. According to the Department of Industry, Science, Energy and Resources, the energy sector (including electricity generation, stationary energy and transport and fugitive emissions from fuels) contributed to 71% of the Australia's GHG missions in March 2020 [25]. Renewable energy applications are developing rapidly both in small scale and large scales in Australia with South Australia leading the way. More than 50% of South Australia's energy produced came from renewable sources in 2019 [26]. With renewable energy penetration increasing, battery energy storage (amongst other storage forms) becomes the critical link between renewables and a reliable, affordable energy future. The renewable energy development in residential and utility scales are discussed below.

Residential scale

Driven by state-based programs, Australia household's battery installation increased dramatically in the past few years with 22,661 batteries installed in 2019 taking Australia's household storage capacity past 1 GWh for the first time [27]. It is anticipated that the costs of energy storage systems will decline by over 25% over the next five years, and hence the levelised cost of electricity from both solar-plus-storage and solar-and-wind-plus-storage are expected to be cheaper than gas power plants in 2025 [28]. This price reduction combined with Government incentive schemes and battery technology improvements are seen as drivers for future ESS battery adoption.

Utility scale

In 2019, Australia's large-scale renewables generation capacity increased by 2.2GW through completion of 34 projects [26]. To support this changing grid structure, in 2019, 15 large scale battery energy storage systems are under construction [29]. The government is targeting 1.2GWh of new energy storage capacity installations in 2020 increasing from 499 MWh in 2019, which will push Australia's cumulative energy storage capacity to 2.7GWh by the end of this year [30]. Neoen announced a 50 MW/64.5 MWh (50%) expansion of the Hornsdale Power Reserve which will allow the installation to provide stabilising inertia services to the SA grid [31]. This will be the first time a large-scale battery has provided inertia services to the Australian grid and is another important step on the transition to a renewable energy future. In January 2020, AGL announced the construction of a 100 MW/150 MWh battery at its Wandoan South Solar Farm in Queensland [32]. AGL and New South Wales Government have lodged a scoping report for a grid scale battery system to build as much as 500MW at its Liddell power plant [33]. In Victoria, Neoen will begin construction of a 300 MW (450 MWh) battery near Geelong and anticipated to come online in the summer of 2021-22 [34].

2.4.2 Landscape of EV adoption in Australia

About 2.1 million electric vehicles were sold globally in 2018 whereas there were only 2216 sales in Australia in the same year [35]. Encouragingly, EV sales in Australia almost tripled in 2019 when 6718 full electric and hybrid plug-in vehicles were sold [36]. During the same period, public charging infrastructure has increased by over 140% [37]. However, this is still far lower than in a majority of other developed countries [38]. Figure 9 shows the electric vehicle uptake in Australia since 2011.

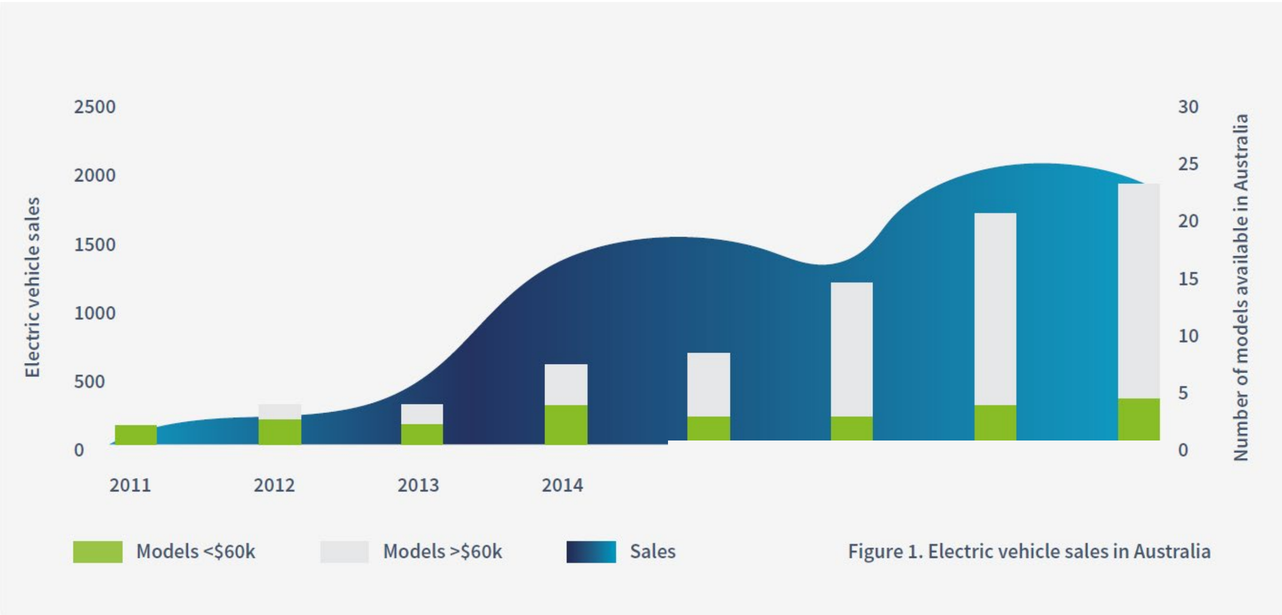


Figure 9 Electric vehicle sales in Australia between 2011 and 2018 [35].

EV uptake has stagnated in the past few years. On one hand, the purchase cost of an EV is high and consumers have concerns about EV driving range; and on the other hand, the consumer purchasing incentives are not significant enough to encourage the adoption of EVs. The small number of users make it challenging for manufacturers to set up high cost servicing centres (over AUD$ 1M) and also discourage EV promotion from dealers as they are not as profitable to service as petrol car [39]. The EV market will only take off when governments introduce supporting policies, for example in the US where the market for EVs is driven by low emission standards. Many States and Territories in Australia are currently developing policies to encourage consumer EVs and replacement of fleets and public transport vehicles with EVs.

2.4.3 Lithium-ion battery waste in Australia

The LIBs used in EVs and energy storage system generally have a long life span of 5-15 years. In 2020, the majority of LIB waste in Australia is from consumer electronics typically from mobile phones, tablets and handheld power tools. According to the Battery Stewardship Council report, 5,290 tonnes of LIBs reached end-of-life in 2017-2018 (however, only 320 tonnes were collected for recycling) [40]. Anticipated EV adoption rates suggest a projected LIB waste generation of

137,000 to 180,000 tonnes by 2036 in Australia [41]. Compared to a 50% collection rate in Europe [42], only around 6% of LIBs, in 2017-18, are collected in Australia and then exported overseas (South Korea, Singapore, Canada and Belgium) for offshore recycling [40]. The option of offshore processing continuing in the future may be questionable and reliant on regulatory or political framework changes. For example, some of the waste receiving/processing countries may decide to introduce a cap on external e-waste/battery-waste due to handling capacity as a result of the large increase in battery use and device size increases with technological advancements and market growth of LIBs driven by EV and ESS applications. This potential scenario has already been enacted for other waste streams such as plastic waste importation restrictions recently introduced by several countries. This provides a key opportunity for Australian industry and progress towards this goal is already underway with the Battery Stewardship Scheme. The Scheme will help address market failures in collection and thereby grow the existing industry and encourage Government and Industry investments that are already underway. Further efforts in this space can help accelerate the collection rate improvements and hence increase waste stream flows to Australian recyclers.

In addition to the environmental and safety concerns highlighted above, the value associated with valuable battery metals and materials used in LIBs is lost from Australian economy. This lost value could be between AUD 4,400 and 17,200/tonne of battery translating to $603 million to $3.1 billion due to the poor LIB collection rates, offshore recycling and landfilling of the LIB battery waste [41]. Further, developing the technology, capability and capacity to process valuable LIB waste on shore is consistent with evolving circular economy thinking and policy in Australia. Effective resource recovery also provides an opportunity to develop on-shore battery materials and systems which align strongly with the Energy Security policies developed and implemented by Federal Government. Although, recycling is not currently part of the energy security policies, there is tremendous opportunity to increase the scope of these policies.

Part III Economics of LIB recycling

Key economic factors for global recycling industry

3.1 Profitability of LIB recycling depending on waste volumes, regions and regulations

LIBs recycling is practised on a small scale globally. According to Technavio, the global LIB recycling only contributed 8.86% of the secondary battery recycling market share in 2018 [42]. LIB recycling hasn't become large scale globally due to economic barriers, largely arising from the current lack of waste stock to feed LIB recycling processes [43] and to some extent because of the complexity of battery design. Similar to LABs, LIBs can be recycled at a high rate, but the issue has simply not yet been viewed as one of critical importance [11] since today, about 80% of LIBs reaching their end of life (EoL) are from portable electronics [44].

While it is currently believed that under the current market conditions LIB recycling processes need subsidies [45]**,** it is claimed that the recycling of lithium batteries will be profitable and convenient given the recent EV boom [46,47]**.** Based on current metal resource pricing and assuming 90% recovery efficacy, it is estimated that the total value that can be recovered from state-of-the-art NMC batteries is over US $7,000/ton of battery waste [46]. According to a recent Forbes newsagency article, relatively few LIBs have reached their EoL because they are relatively new to the market and have long cycle life [11]. Therefore, LIB recycling will likely become significantly more viable with large amounts of EVs, ESS and industrial LIBs flowing into the e-waste stream after reaching their EoL.

The global EV battery reuse and recycling market generated $61.5 million in 2018 and is estimated to reach $7, 809 million by 2025 with a CAGR of 99.8% [48]. Apart from the volumes of battery waste available for processing, there are other factors that complicate the economics of LIB recycling. According to Wang et al. [49] A well-functioning collection and recycling infrastructure is critical to minimise associated environmental impacts. The Consortium for Battery Innovation pointed out that the volume of lithium battery production is relatively low in North America and therefore the materials recovered from LIB recycling processes would likely have to be exported to other countries, such as China [56]. Although in China the manufacturing rate is relatively high, spent LIBs either end up in landfill or are stockpiled in warehouses without proper handling because no proper disposal and collection schemes are in place [50]. South Korea as one of the major LIB recycling regions reported collection of the EoL LIBs, and an extended producer responsibility (EPR) policy were adopted for battery recycling in 2003 [51].

A survey of ~50 global LIB recycling companies found about 100,000 tons of LIBs were recycled globally in 2018, of which 67,000 tons were recycled in China and another 18,000 tons in South Korea [44,52]. The 100,000 tons of waste LIBs represents about 50% of what reached EoL in those jurisdictions [53]. China and Korea are preferred destinations for LIB waste since they pay a much higher price for waste LIBs than other businesses in Europe and the US, because they achieve higher recycling efficiencies. Without government regulation and proactive policies and incentive schemes to help keep the waste locally, competitive price-based waste purchase and development of economic recycling processes, the LIB or EV battery recyclers in America and Europe, despite having efficient processes will struggle to acquire the volumes of waste batteries required for profitable operations [54].

It is also critical to the battery recycling industry to have a well functioning collection infrastructure. This infrastructure serves to help minimise environmental impacts through diversion of recyclable battery wastes from landfill sites. Additionally, the infrastructure also serves to assist recycling and resource recovery industries to have a stable supply of waste. In many jurisdictions, where LAB and e-waste recycling is regulated (which includes Australia), there is an incumbent collection network for these wastes. Thus, an opportunity exists to expand and leverage this existing infrastructure to encompass LIB waste and build on the success of the e-waste and LAB collection networks.

3.2 Economics of LIB recycling depending on battery chemistry

According to the Circular Energy Storage's latest data, more than 1.2 million tons of waste LIBs will be recycled worldwide by 2030 [55]. By then the amount of recycled lithium available to the global battery supply chain will be equivalent to about half of today's lithium mining market, while the amount of recycled cobalt in 2030 will be around a quarter of today's equivalent [55]. The profitability of LIB recycling is dependent on the monetary value of a number of key components. The composition range of LIBs along with commodity values is summarised in Table 3, whilst the historical price trends of these elements and a cost breakdown for LIB manufacturing are shown in Figure 10.

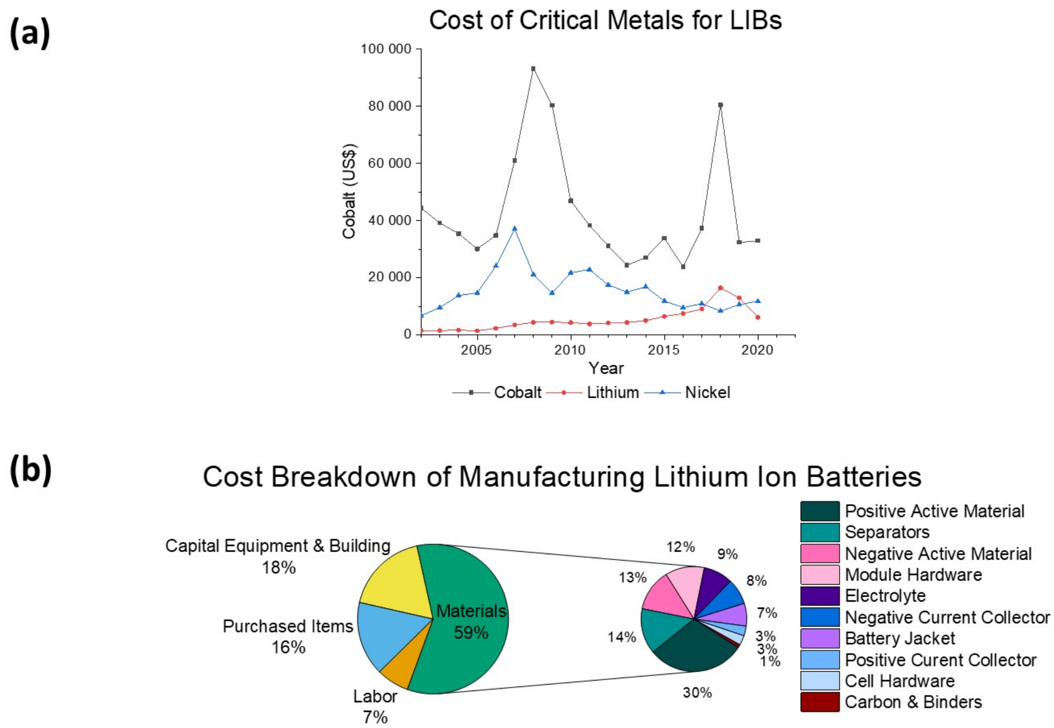


Figure 10 (a) Historical price of Cobalt, Nickel and Lithium between 2002 and 2020. Data from [56,57]. (b) Cost breakdown by percentage for making lithium-ion batteries. Plotted based on reference [58].

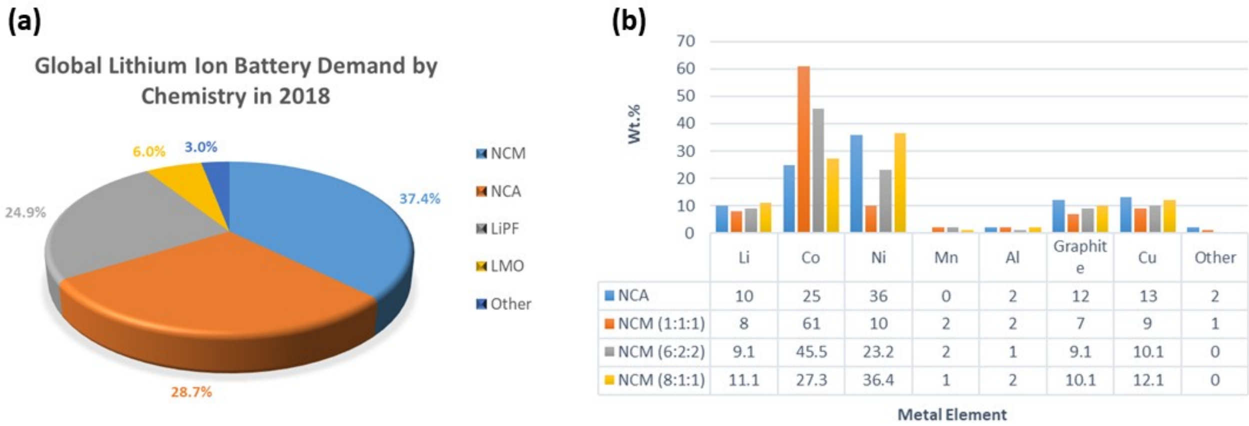
A modern nickel-manganese-cobalt (NMC) LIB comprises about 7% Co, 7% Li, 4% Ni, 5% Mn, 10% Cu, 15% Al, 16% graphite and 36% other materials, where lithium is expressed as lithium carbonate equivalent (1 g Li = 5.17 g LCE) [59]. Most of the current LIB recycling processes and research is focused on the recovery of high value elements such as Co, Ni and Li to a high purity level that allows for their reuse in battery manufacturing. However, the modelling of LIB recycle processes is complicated by strong fluctuations in the stock market value of commodities. A most striking example is the price for cobalt which, according to Figure 10a, fluctuated between below $US 40,000 and 100,000 from 2005 to 2020. By contrast the lithium price during the same period steadily increased until 2018, then dropped by 51% and its price is predicted to slide despite forecast supply disruptions and strong demand growth in the future due to “excess” supply [60]. Depending on the purity and prices, if battery manufacturers chose mined over recycled raw materials, this would force recyclers out of business. “Lithium supply is growing far quicker than lithium demand and this can be said for all battery materials as the EV pick up rate is not expected to really start increasing until the early to mid-2020’s,” said Marcel Goldenberg, manager for metals and derivatives at S&P Global Platts [61]. The oversupply of mined lithium products was mainly caused by the commissioning of lithium mineral operations in Australia outpacing mineral conversion capacity in China [61]. The commissioning of four lithium mineral projects in Australia and Brazil, coupled with the ramp-up of production at several existing brine and mineral operations was responsible for the increase in capacity [60].

Table 3 Component range of typical LIBs and current commodity value of each metal element in 2020.

Component	Composition[a] %	Commodity value[b] US$/tonne
Cobalt	5-20	41,250
Nickel	5-15	17,647
Lithium	1-7	62,500
Manganese	10-15	31
Iron	5-25	158
Aluminium	4-24	1,961
Copper	5-10	3.5

a) Data from reference [62]; b) https://tradingeconomics.com/commodities, accessed on 2nd February 2021.

The cost breakdown for LIBs is shown in Figure 10b. Cobalt, amongst the other metals present in common cathode formulations, accounts for up to 60% of the cathode cost [63]. The overall cathode material formulation alone counts for 30% of the battery material cost [64]. In order to reduce the battery raw material cost, batteries comprising of NCA cathodes with much less cobalt (cf. NMC) and cobalt free LFP batteries have become more preferable in the LIB market. Recently, Chinese battery manufacturers such as CATL and BYD, have increased their nickel to cobalt ratio in battery cathode materials to 10:1. Figure 11 shows the market demand of different LIB chemistries in 2018 as well as their different metal compositions in wt%. NMC, NCA and LFP are the top three chemistry types. According to several market forecasts, nickel rich cathode materials such as NMC and NCA will be in high demand due to the higher energy densities that can be achieved with these materials and will be the mainstream chemistry to gain market share against LFP batteries [65]. For most of the cathode chemistries containing Co and Ni, the recovery makes economic sense. But for cathode materials, such as LFP and lithium manganese oxide (LMO), the constituent metal value is very low according to the metal price listed in Table 3. Another point to consider from the current trend of using cheaper metals for LIB manufacture is that it will make the LIB industrial recycling less profitable in the future under current processing and business models [66]. Except for the above mentioned chemistry shift, another long term financial concern for the recycling industry are the challenges associated with emerging alternative lithium battery chemistries, such as lithium sulfur and lithium air, or a different vehicle propulsion system, like hydrogen-powered fuel cells. These developments could diminish the growth and impact of the projected EV market in the near future and therefore sustainability of recycling LIBs [18]. For example, in Q4 2017 when the Japanese government and automakers started to promote hydrogen fuel cell vehicles a drop in EV sales from 2018 was observed [48]. However, the current hydrogen fuel cell technology has several barriers to overcome before it can compete with EVs [19]. The impact of low cobalt LIBs and possible solutions was discussed by Gaines recently [67] where the profitability of recycling low cobalt content LIBs will depend on the advancement of recycling technology, rely on subsidies and/or government regulations [67].



	Li	Co	Ni	Mn	Al	Graphite	Cu	Other
NCA	10	25	36	0	2	12	13	2
NCM (1:1:1)	8	61	10	2	2	7	9	1
NCM (6:2:2)	9.1	45.5	23.2	2	1	9.1	10.1	0
NCM (8:1:1)	11.1	27.3	36.4	1	2	10.1	12.1	0

Figure 11 (a) Global lithium-ion battery market share by chemistry. (b) The material composition weight percentage breakdown of NCA and NCM lithium-ion batteries. Plotted based on data from reference [63].

3.3 Reducing recycling cost by reuse of LIB in second life applications

Another way to contribute to a sustainable battery value chain is to use of batteries with as much of their existing structure/pack as possible, which applies to battery packs in particular, where intact cells may be segregated from damaged cells. This is called second-life, after repurposing the battery for a less demanding application. Currently, LIBs are at the end-of-life when they are unable to continue to sufficiently power an application or a device. From a chemical perspective, a LIB still contains significant energy storage capability, often 70-80% of the initial capacity is still available at the common cut-off threshold in EV applications. Some spent EV batteries even have 90% of initial capacity. This is typical for batteries retiring from commercial EV fleets which is currently the dominant EV application in Australia. The second use may be economic for some batteries and applications, but not all. It was suggested that cobalt-containing batteries should be recycled immediately to boost the cobalt supply whereas other battery types seek opportunities to be reused [68]. Despite the obvious attraction of residual energy, the interest in reuse (or repurposing) has only started to gain momentum since the growth of and supply of large EV batteries has risen significantly and recycling of these batteries has yet to be properly established. Thus, second-life use has been seen as economically and environmentally viable means to address this waste stream, until a functioning battery recycling program can be established.

The LIB waste stream from EVs consists of 25% of Battery Electric Vehicle (BEV), 36% long range Plug in Hybrid Electric Vehicle (PHEV) and 39% short range PHEV battery packs in United States

[69]. Although LIBs are dominant in today's EV battery market, the concept of reuse or second-life of EV batteries is not limited to LIBs. Sandia National Laboratory studied the techno-economic viability of using second-life NiMH EV batteries and found that reusing NiMH EV batteries in secondary applications is technically feasible [70]. The foreseen advantages of pursuing battery second-life is illustrated in Figure 12. Similar to LIB recycling, the reuse of EV batteries presently is also complex due to numerous market and technical challenges, (discussed later).

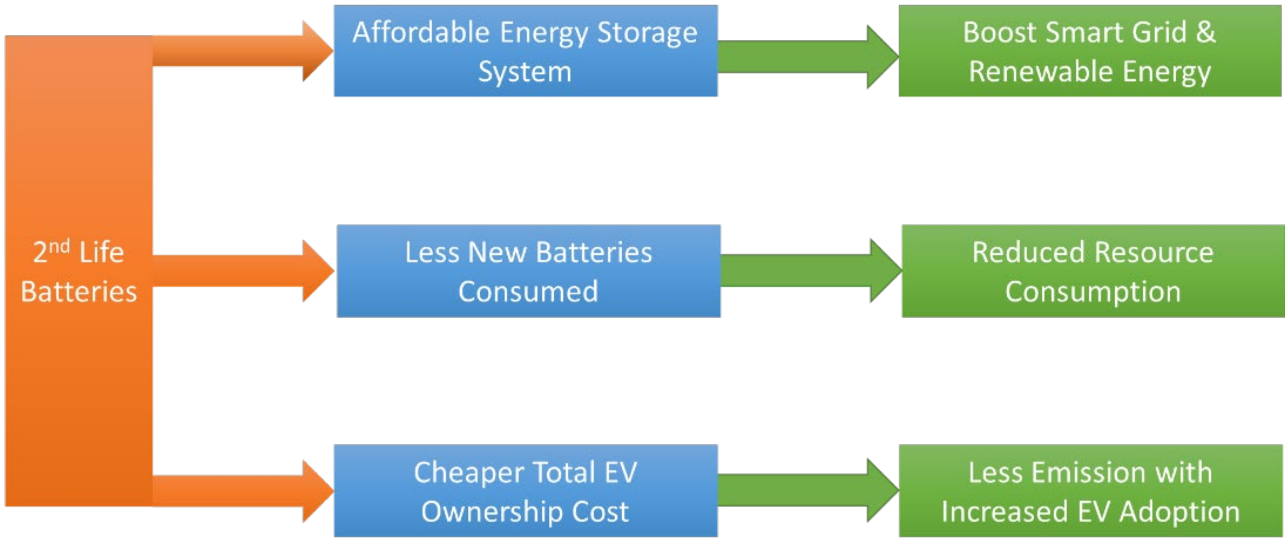


Figure 12. Summary of the primary advantages of using the second-life EV batteries.

3.3.1 Sources and criteria for EoL EV batteries

The global stockpile of EoL EV batteries is forecast to exceed 3.04 million packs by 2025 compared with 44,000 in 2018 and it's estimated about 20 million EVs will be sold globally by 2025 [48]. An average EV battery has a life span of 8 to 12 years. Therefore, the share increase in sales of EVs since 2010 is providing a good source of second-life EV batteries as the first generation of retired EV batteries are starting to enter the market. The EoL for EV batteries was first defined by the US Advanced Battery Consortium (USABC) in 1996 as a 20% drop of cell capacity from the rated value, or a 20% drop from rated power density at 80% depth of discharge (DOD) [71]. The suitability of the criteria remains questionable since they were established when most EVs were powered by nickel-based batteries [71]. Another simulation study by Saxena et al. [72] also showed that batteries at 30% of initial capacity can meet the driving need of Americans. They demonstrated that the current EoL EV batteries criterion may be unrealistic as the batteries with 80% remaining capacity are still able to cover the daily travel needs of more than 65% of US drivers [72]. As these studies were carried out by simulation without considering the battery degradation, more relevant physical work is needed to help improve the definition of the retiring criteria of EV batteries [73].

Furthermore, under-utilisation of batteries is common in many industries, and this leads to discarding a large amount of capacity (or electrical energy) from reasonably healthy batteries. Therefore, the EoL EV batteries can be categorised into: type 1) reached the end of their first life through the general process of capacity loss; type 2) the vehicle service life ends before the batteries reach the end of their first life. When a battery retires and enters into the secondary life market it is tracked on the Battery Ownership Model (BOM) [74]. The three main BOMs are:

- The EV manufacturer (OEM) is the battery owner and the EV owner leases the battery from the EV manufacturer.
- Third party owns the battery and the EV owner leases the battery from the third party.
- The EV owner is the battery owner.

For the first two BOM scenarios, the retired battery will most likely have about 80% capacity based on battery performance or defined warranty period. When the EV owner is the battery owner, the battery would only be changed when they are unable to satisfy the customer's need, and therefore are expected to have much less capacity than the recommended 80% threshold. Retired EV batteries could also have higher than 80% capacity if they are from early vehicle failure, e.g. major repairs, collisions etc. [75]. The above-mentioned battery retirement scenarios lead to a wide range of SLBs with different residual capacity and internal resistance values or even different numbers of full-equivalent cycles. The capacity and internal resistance certainly will impact on the value of the retired battery and the refurbished second-life battery market price [76]. The USABC is planning to introduce a minimum standard battery life of 15 years [77].

3.3.2 The price challenge of second-life batteries

Sandia National Laboratory have studied the cost of second life batteries in detail [70]. The percentage breakdown of various sectors is shown in Figure 13a. It was identified that the cost of SLB acquisition is the most expensive part accounting for 56% of the total second-life battery cost [70] amongst additional cost for labour, general & administrative (G&A) and packaging material. Labour costs and general administration are the second biggest cost with each contributing 13% to the cost of battery refurbishment. Whereas another cost study by McLoughlin et al. [78] showed that transportation costs are the second most prominent expense. This may be the result of different definition or classification of the cost components in the two studies. The cost of SLB acquisition could already include the transportation cost, which together with battery materials becomes the biggest overall cost. The labour cost analysis conducted by Sandia National Laboratory was based on the US market and therefore the labour costs may be as low as 5% in other countries according to Figure 13b. Since general administration is also a labour related expense, it is reasonable to assume that the total battery refurbishment cost could be about 20% less in countries having much lower labour cost compared to the US.

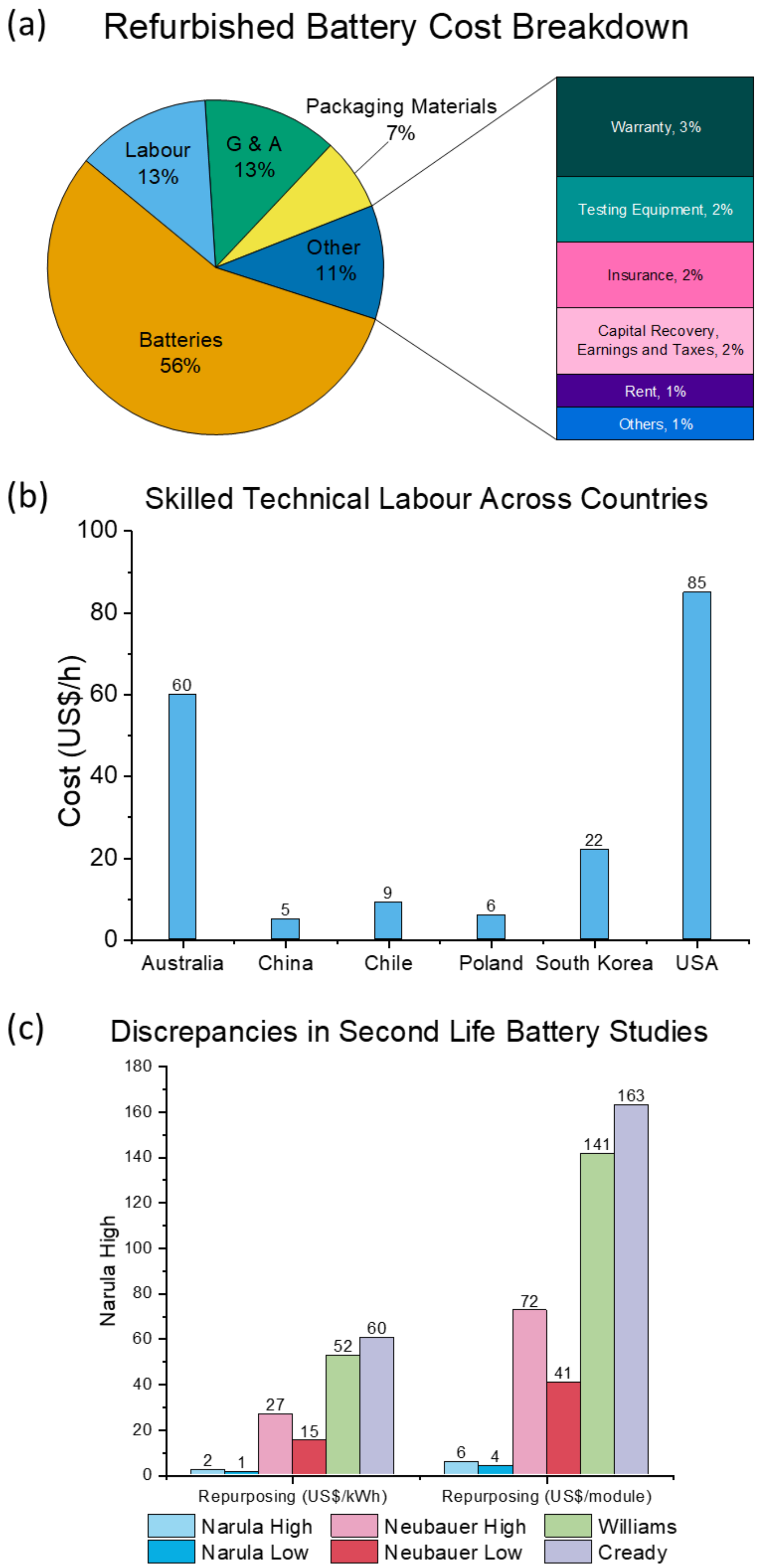


Figure 13. (a) Cost breakdown of second-life EV batteries in percentage [70]. (b) Labour cost in different regions according to [42]. (c) Discrepancy in different cost studies of battery repurposing [79].

There is a large discrepancy in the battery repurposing cost amongst different cost studies [79], which is summarised in Figure 13c. The second-life battery market price, salvage value and refurbishment studied by Neubauer et al. [80] are in between the highest and lowest cost estimates and are summarised in Table 4.

Table 4. The second-life battery market price, salvage value and refurbishment cost [115].

New Battery Price [US$/kWh]	Second Life DoD	Vehicle	Health Factor	Max Repurposed Battery Selling Price [US$/kWh]	Used Battery Salvage Value [US$/kWh]	Cost of Refurbishment [US$/kWh]
250	60%	BEV75	0.33	83	51	32
		PHEV20	0.29	73	43	30
	50%	BEV75	0.72	180	131	49
		PHEV20	0.65	163	117	46
150	60%	BEV75	0.33	50	24	26
		PHEV20	0.29	44	19	25
	50%	BEV75	0.72	108	72	36
		PHEV20	0.65	98	64	34

The market price for the SLBs ranged from 44 to 180 $/kWh based on Neubauer's analysis. Neubauer found that repurposing costs can be as low as $20/kWh if vehicle diagnostics data is available and can be used to support used battery purchase [80]. Because technician labour is a major cost component of the repurposing operation, it is economically impractical to replace faulty cells within modules, therefore minimising purchases of modules containing faulty cells is critical. There will also be additional costs due to the testing of EoL batteries to identify suitability for second life use. These costs will strongly depend on the original battery pack design (including battery management system software access) and cell/module accessibility.

One of the main threats to the emerging second life industry is in the continued price drop of first life batteries. Second life batteries face medium to high repurposing costs under current processing methods. However, estimates suggest that at the targeted second life battery market price of $50/kWh (vs. 150 to 200$/kWh for new batteries currently), second life systems will remain competitive until at least 2025 [48]. Improvements in reprocessing technology can extend this competitiveness into the long term future.

Part IV State of art and technical challenges of LIB recycling and reuse

A gap analysis on the current LIB recycling technologies

4.1 LIB recycling process

Currently, the majority of end-of-life LIBs are from consumer electronic sources (approx. 80% of total waste) [40]. Consumer electronics batteries are small in size and low energy which makes it easy for recyclers to treat them utilising the well developed techniques [50]. However, large EV and ESS batteries, generally contain several hundred cells grouped in modules and typically still contain up to 60-80% initial energy capacity. In order to access the cells for recycling, significant disassembly of these systems is required, which is complicated by non-standard design and disassembly procedures between differing battery manufacturers. Hence, recycling of large LIBs inevitably faces more challenges than the smaller consumer electronic LIBs. The current state of art technology and technical challenges will be reviewed and discussed in the following sections.

During collection, most spent (waste) LIBs are aggregated as a mixture of different sizes, formats and application types. Due to poor labelling by manufacturers these aggregates can also contain a mixture of different LIB chemistries [51]. Battery packs are not disassembled during collection to cell level. This means that manual sorting and disassembly is required to separate the LIBs into pure waste streams segregated by LIB chemistry type prior to further processing. Depending on the downstream processing for metal recovery (and consideration of the recovery of other value-added products), pre-processing of LIB waste usually consists of discharging (submersion in saline solutions for 24 h); manual dismantling and sorting (removal of plastics and casings); crushing, milling and screening (selective separation of aluminium and copper). Further pre-treatment, including some chemical (wash) and thermal processing may also be required prior to recovery of resources [82], dependent of specific recovery processes. From the pre-treatment, electrode materials are gathered which are used as input material to separate metal elements, followed by recycling separated metals. The LIB recycling steps are illustrated in Figure 14.

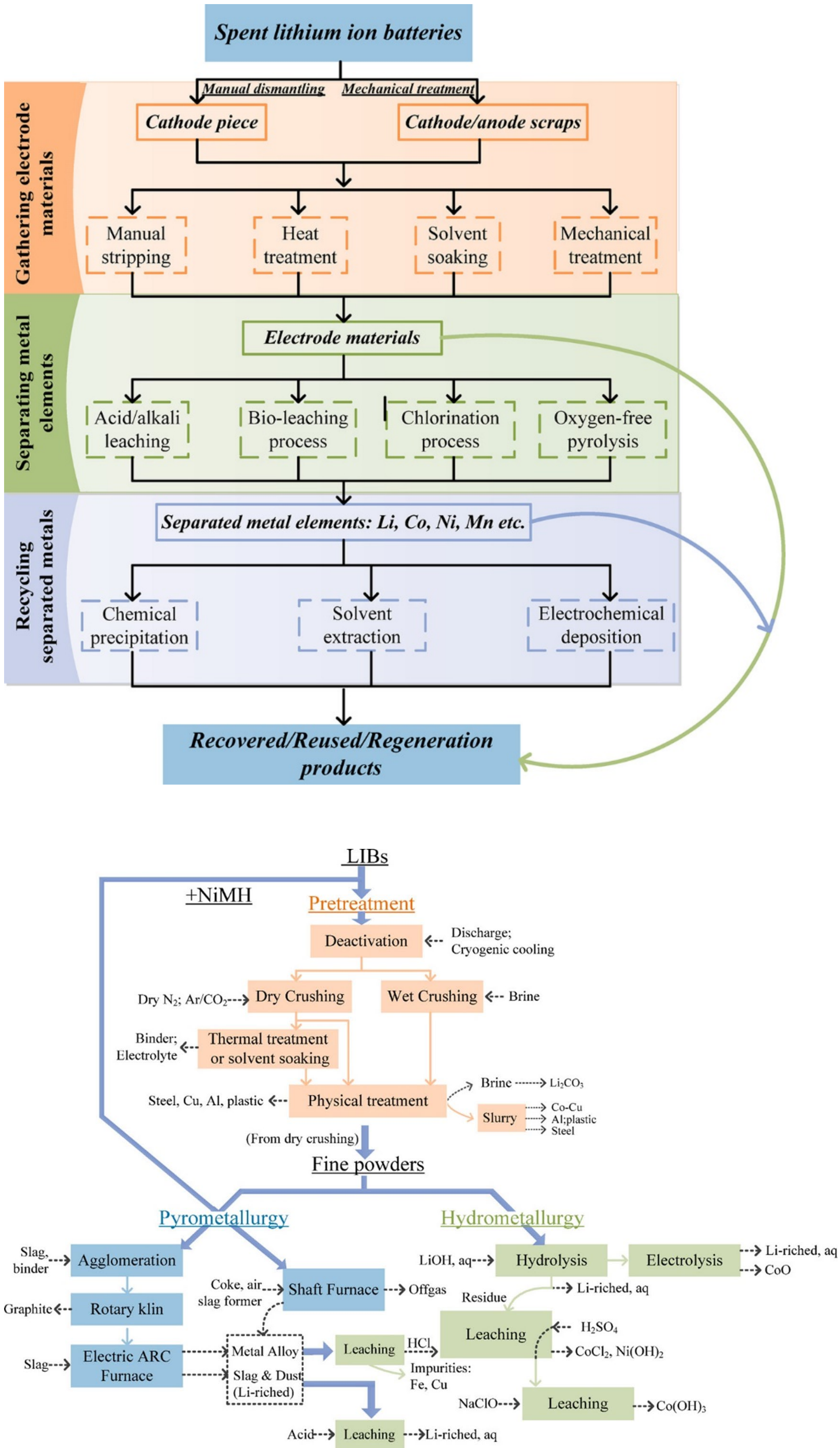


Figure 14 Spent lithium-ion battery recycling process steps (top) and detailed processing steps (bottom) [83].

4.2 Sorting, discharging and dismantling of LIBs

4.2.1 Sorting

Aggregation of batteries during collection means that prior to recycling, the mixed batteries need to be separated into pure waste streams, segregated by chemistry type. This is especially important for LABs where the inclusion of LIB waste can pose significant safety and fire/explosion hazards during LAB processing. One of the key challenges in sorting spent LIBs is identification of cell chemistry type due to a lack of proper labelling or signage on the cells. This means that use of automated separation techniques such as AI and robotics, is somewhat challenging. Ideally if the LIBs have a unique identification, or so called battery passport, it will make the sorting as well as battery waste tracking much easier. It is possible to use blockchain, artificial intelligence (AI) and robotic technology to provide full life cycle tracking of battery materials and China has signalled its intention in this area [84]. Interestingly, battery tracking is also a great interest and strong suggestion from the battery reuse community.

Discharge

Batteries in landfill or recycling plants can easily be damaged or short circuited, which leads to potential for fire or explosions. There are a number of different strategies being investigated or utilised currently for managing the fire risk, however, none of these methods is easy to deploy and hence act as a panacea for the battery recycling industry. One such method is discharging the LIBs to a safe operating voltage prior to entering waste stream for recycling. At present, this is not performed by the last person to use the battery prior to end-of-life and hence many LIBs in the waste stream can contain significant quantities of energy and hence have a potentially significant fire risk. This fire risk is exacerbated when further disassembly is required, hence LIBs require to be discharged to ensure safety during recycling and resource recovery operations.

It should be noted, that although the battery recycling sector is focussed on the safety risks of used batteries the sector is not yet fully prepared to deal with the additional risks arising from EV batteries. For this emerging waste stream there needs to be greater collaboration between original equipment manufacturers and the recycling sector to ensure safety of used EV batteries. Although this is easier to apply for batteries removed from vehicles by manufacturer authorised engineers, there is still work to be done to educate and provide support for third party removalist (for example scrap yards, non-manufacturer affiliated mechanics etc.).

There are two methods widely utilised for battery discharging prior to recycling. One is relatively straightforward and simple by wet chemical process, where a chemical solution with a high ionic conductivity (typically salt in water) is used to short circuit the battery. By controlling the ionic conductivity, the short circuit current, and hence rate, can be controlled to a safe operating limit. For large batteries, it is awkward and risky to perform the discharge via wet chemical method due to the high residual energy and physical size and weight of the devices. The other method is electrical discharge which is more difficult to achieve. The main difficulty arises from a range of different battery sizes and designs and a non-standardised electrical connection point on batteries. This non-standardisation, and in many instances company specific connection designs and in some instances communications protocols with energy or battery management systems, means that any discharging technology must be able to cope with a wide range of different designs. Further, different batteries have different electrical performances and operating limits, depending on how the battery pack has been setup. Hence the discharging technology must also be able to cope with this wide range of sizes to be utilisable in a real-life application. CSIRO has recently developed an electrical discharge systems that can deal with any type of batteries and readily fit into industry process handling. In order to offset the cost of deployment of such a system, as well as improve the business energy sustainability, this battery discharge device is also designed to be able to capture the electrons from the discharge process and feed into the recycling plants daily electrical loads. This function reduces the overall electricity use of the plant, thereby reducing the electricity costs whilst simultaneously improving safety and sustainability.

Some recyclers will perform a partial disassembly to expose larger battery pack terminals and then utilise a resistor or wire across terminals to short circuit batteries under semi-controlled conditions. This is not a recommended procedure and has a high safety risk of harm to the workers and potential to cause fires or explosions.

Recycling infrastructure suppliers are beginning to address this discharging issue through utilisation of inert atmospheres during the initial crushing/cutting process in an effort to provide the short circuiting under controlled conditions and hence incorporate both the discharge and crushing processes into a single step. It should be noted, that for specific resource recovery processes, such as pyrometallurgy, the discharging is not required. The operating temperature of a pyrometallurgical process is sufficiently high that smelter design can easily accommodate battery fires which burn at lower temperatures than the smelting process. As such the smelters safety features can inherently accommodate any risks due to battery fires.

4.2.2 Disassembly

For small batteries, such as those from consumer electronics, disassembly is typically not performed and the devices are placed into a crushing and screening process to separate the battery materials and other components. For larger battery packs, such as EVs or ESSs, this is not a feasible approach and a different process is utilised. For these devices, the recycling process starts with discharging the spent batteries in salt solution and drying followed by disassembly of the batteries down to module or cell (we note that this is only one option and the industry is also exploring a range of alternative options as well for safe recovery). This allows separation of the different battery components such as cells/modules from other hardware such as battery management systems, inverters, packaging, plastics etc. The automation of the dismantling of EV batteries presents major challenges. In the manufacturing sector, robotics and automation are performed in highly structured environments, where robots make pre-programmed repetitive actions with respect to exactly known objects in fixed positions. In the recycling case, the robotic systems need the ability of handling a variety of objects and high levels of uncertainties. This is due to there being no standardisation of design for LIB packs, modules or cells within the automotive sector [84]. As such each manufacturers vehicles battery pack is different from competitors and can change design and chemistry in between models and manufacturing years. As a result, robotic disassembly remains a major challenge at the frontier of artificial intelligence research. There is some progress towards the automated sorting of consumer batteries, such as Optisort system [85], however it is currently limited to AA and AAA batteries and a large amount of manual pre-sorting is still needed prior to entering the Optisort machine [85]. As the recycling of large EV batteries is very expensive under the current recycling techniques [86], reuse of EV batteries is considered an attractive option for auto and batteries makers. It was reported that recycling companies can make only $^1/_3$ to $^1/_2$ of the recovery costs by selling recycled critical materials [86].

4.3 Metal recovery

4.3.1 Pyrometallurgy

The pyrometallurgical process extracts metals by heating electrode parts to form alloys. Lithium can be recovered by leaching but the cost and energy requirements is not economically favourable (at current lithium prices) [68]. The pyrometallurgy method requires less pre-treatment of battery scrap, therefore, has the advantage of having the lowest cost. However, burning plastics will release dioxins, which are classified as a highly hazardous material and lead to secondary pollution issues [87]. Except for the waste gas, the pyrometallurgy process also suffers from the waste slag, high energy cost due to mechanical treatment and some metal loss [83].

4.3.2 Hydrometallurgy

Hydrometallurgy provides a more specialised method for the recovery of metals from complex metal-containing wastes. Metals are recovered through leaching and extraction at low temperature. The advantage of hydrometallurgy is its high recovery rate, lower energy consumption compared to pyrometallurgy and ability to cope with low metal ion concentrations. The downside of hydrometallurgy is it has many more process steps than pyrometallurgy [83]. Currently, the majority of the recycling companies are adopting the pyrometallurgical process, mainly due to the lower cost and scalability [87]. It’s becoming more favourable to use the hydrometallurgical process as higher value derived from metals recovered can cover the processing cost and hence create an economically viable business model [87]. Pyrometallurgical and hydrometallurgical processes can be mixed to deal with waste recycling. Umicore and BATREC are the major companies adopting pyrometallurgical process. In China, more than 70% of the recycling processes are primarily hydrometallurgical with the rest of 30% accounted for pyrometallurgical combined with mechanical processes [86] . Figure 15 illustrates the technologies adopted by major global EV battery recycling companies.

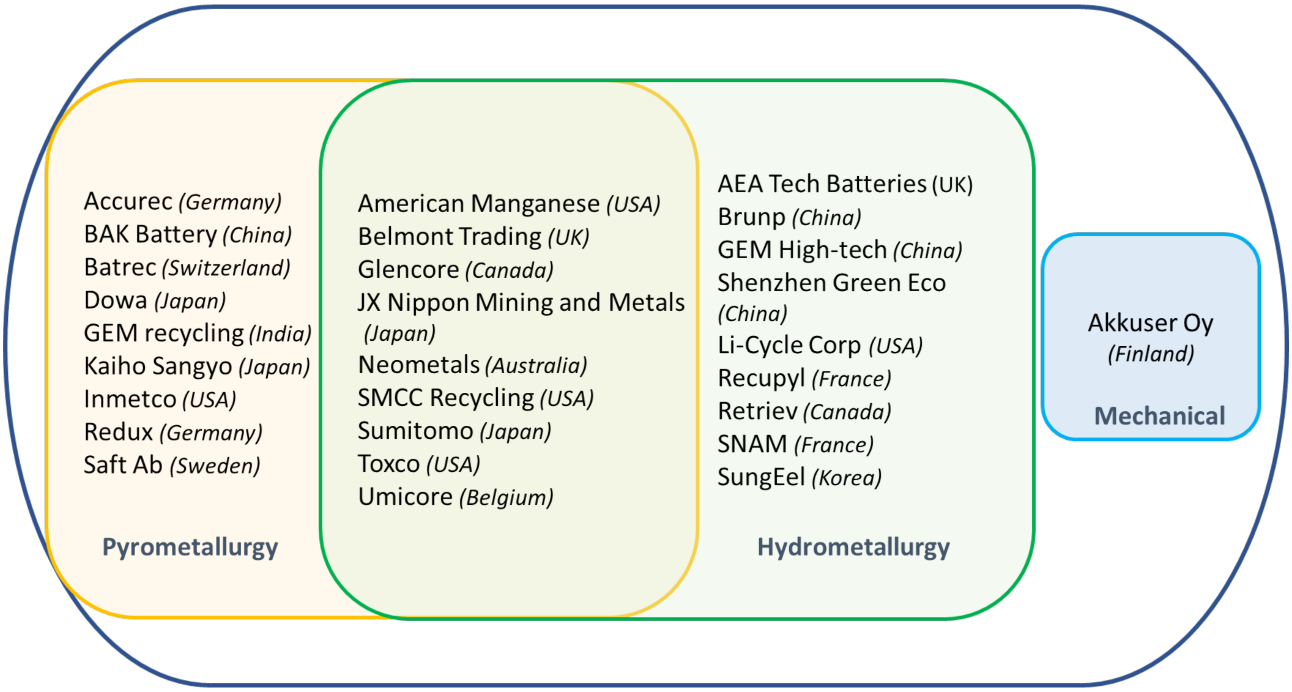


Figure 15 Technologies adopted by major global EV battery recycling companies [86,88].

Following the solubilisation of metals from waste LIBs by hydrometallurgy-based processes, complex and mixed metal solutions are generated that require further processing to separate and purify constituent metals. Regardless of the metal solubilisation method employed, the recovery of metals from the complex metal-containing leachate solutions can be challenging, due to complex chemistries and co-digested compounds associated with binder and other materials if they are not appropriately removed. To separate pure metal fractions, the use of various separation and extraction methods or sequential separation and extraction is required. Here, methods such as solvent extraction and electrodeposition are used in combination to produce pure metals or alloys, or precipitation of metal species using hydroxides, sulfides and other complexing agents, which can then be further purified or refined.

In case of chemical precipitation, sources of hydroxide or sulfide ions or complexing agents are added to the solution and the pH, if necessary, is adjusted using caustic soda or lime to promote the precipitation of metals at increasing pH set points. In most instances though, co-precipitation of metal species often occurs when adjusting pH because of the similar chemical properties of these metal ions in solution, resulting in only semi-selective or non-selective separation of metal species. [89,90]. Since lithium-ion does not precipitate under these conditions and remains in solution, it is separated with relative ease from all other metals and can be recovered conveniently by precipitation as lithium carbonate [89,91] or hydroxide. Recovered metal ion precipitates then require further processing for the production of pure metal salts, metals or mixed metal alloys.

Efficiencies of extraction are determined by the initial composition of the solution, the combination of the extractants used and the extraction conditions, particularly pH [92,93]. Using various types of, and combinations of, chemical extractants, solvent extraction has been demonstrated as a method for the separation and purification of metal species from waste LIBs [94,95]. However, challenges exist in trying to separate out the valuable metal ions cobalt, nickel and manganese from solution due to their similar chemical properties. In some studies, the purification of these metals has been improved using the combination of solvent extraction and membrane separation [96]. Driven by electrochemical reduction reactions, metals can be separated and purified from solutions generated by leaching waste LIBs. Electrodeposition, including electroplating for production of pure metals and alloys, has also been attempted as a method to recover metals from waste LIB leaching solutions [97-100], but in most cases electrochemical recovery studies were limited to single metal electrode materials. To date, separation of these three key metal ions solely by electrochemical means has not been achieved.

4.3.3 Direct recycling process

Direct recycling is also called cathode to cathode recycling which is particular attractive for batteries with high values elements in the cathode. The main difference between hydrometallurgy and direct recycling process is that hydrometallurgy uses strong acid to dissolve the cathode into the aqueous solution whereas direct recycling retains the cathode crystal morphology. However, as the feed waste stream will be a mix of different types of battery chemistry, the direct recycling will lead to the generation of a mixture of cathode materials. Unless the retention of structure of cathode mixture are found useful, there is no clear advantage from direct recycling approach under present battery manufacturing processes.

4.3.4 Biological processing

Biological processing is another way to extract metals via microorganism leaching. Driven by green and low secondary pollution, biological or bio metallurgical process have earned more attention during recent years [101]. However, it is hard to use in large scale due to lack of cultivation medium [87]. There is the potential for Australia to utilise its existing expertise in the agriculture industry and transition into this processing method, however, research support would be required for that industry.

4.4 $LiPF_6$ electrolyte salt recovery

Fluoride or fluorinated compounds inevitably present in LIB electrolytes, can hamper or even damage recycling processes in industry and have to be removed from the solid LIB parts, as well. Hence, the electrolyte containing the $LiPF_6$ salt represents a target component for the recycling of LIBs. Additionally, the recovery of $LiPF_6$ can assist the economics of LIB recycling due to its current high commodity value. The common lithium source in LIBs, $LiPF_6$, is a high value material, difficult-to-synthesise and hence worthwhile to recover. It is noted in the literature [102] that electrolyte recovery processes may be further complicated by the presence of phosphorus oxy fluorides, POFn, which are generated in the presence of traces of water. Furthermore, the hydrolysis products can react with the organic carbonate solvent to generate various organophosphate-based and organic fluorophosphate-based aging products. The formed organic fluorophosphates have a high potential toxicity; i.e. dimethyl fluorophosphate (DMFP) and diethyl fluorophosphate (DEFP) are classified as toxin category class 1 by the WHO [103].

Lab-scale and commercial LIB recycling processes are focused on metals such as Ni, Co, Cu and Mn whereas lithium may be recovered in hydrometallurgical processes from the cathode active material, however only in the form of Li_2CO_3, LiOH and the like. Particularly in pyrometallurgical processes the electrolyte and lithium thereof is not recovered but simply combusted or disposed of during the process. Hence the handling of electrolytes is rarely mentioned in the current literature.

Two papers, by Novak & Winter [102] and Rothermel et al. [104], discuss the stepwise electrolyte recovery (with an extractant) along with valuable graphite (by thermal treatment) at the front end of the process (post-discharging, pre-leaching). Electrolyte removal was achieved by three different methods, (i) extractive washing with N-methyl pyrrolidine (NMP) and ethanol (EtOH) followed by drying, (ii) extraction with supercritical CO_2 and (iii) extraction with subcritical CO_2/acetonitrile. After removal, the graphite powder was thermally treated and used to create new anodes (see below). Novak et al. [102] describe the quantification of recovered electrolytes and their composition following extraction with sub- and super-critical CO_2. They also argue that the removal of the electrolyte solutions will abate downstream release of fluorinated compounds and further suggest that this method could play a role in analysis of electrolyte aging and for post-mortem battery cell investigations more broadly.

CSIRO has developed a simple and cost-effective way to recovery lithium-ion battery electrolyte. A patent for this technology was filed to support future commercialisation. Process scale-up is underway. Future investigation shows the recovered electrolyte salt can be directly used to make new LIBs. The new LIBs produced with recovered electrolyte salt shows no performance difference to commercial electrolytes.

4.5 Anode (graphite) recovery

Graphite can be recovered prior to, or after, hydrometallurgical processing for metal recovery. It is not possible to recover graphite if LIB waste is processed by pyrometallurgy-based processes, as the graphite is generally lost during the thermal treatment of the waste. The literature describes recovery of graphite immediately after LIB waste has been dismantled, prior to hydrometallurgy, as well as after metals have been removed by hydrometallurgical processing [105].

Recovery of graphite prior to hydrometallurgy requires the removal of electrolyte and these processes are usually undertaken in sequence, prior to metal dissolution [104]. For their work, the authors used simulated end-of-life batteries (Panasonic, NMC) from which the cathode and anode part were separated manually under inert gas (helium) conditions. According to this account the presence of electrolyte is the biggest challenge for graphite recovery. The electrolyte is recovered under inert (oxygen and moisture free) conditions, followed by thermal treatment of the graphite at temperatures around 1000 °C to remove the binder and residual solid-electrolyte interphase (SEI) components by thermal decomposition. For the manufactured anodes from the recovered graphite it was shown that the best performance of this secondary anode material is achieved when the extraction of excess electrolyte is done with subcritical CO_2 ($scCO_2$), but this processing did adversely affect the crystallinity of the recovered graphite. This has implications when considering the re-use of recovered graphite for making new anode materials. Literature has shown that the change in crystal structure doesn't change the capacity of secondary anodes [104]; however, it is not clear what impact the change in structure has on the re-charge and charging cycles, the lifespan or quality of LIBs that can be manufactured from these recovered materials.

Recovery of graphite following the separation of metals using hydrometallurgical processing, simply focuses on the purification of post-leach residues to recover the graphite. It is likely that the residues will also contain small amounts of metal salts remaining from leaching processes, and to our knowledge, this method of graphite reclamation, purification and re-use has yet to be demonstrated in the literature. Though the graphite recovered may not be pure enough for the manufacture of secondary anodes, there is still potential to re-use it for applications such as water purification and filtration [92].

4.6 Feasibility, challenge and economics of second-life LIBs

The use of batteries after they have reached the end of their first designed useful life is termed as second-life. Battery reuse is typically the domain of large end-of-life batteries as it makes little economic sense of exploring the second-life of small size batteries from consumer electronics. The lithium-ion battery reuse will only start to gain momentum when the supply of large EV batteries grows significantly and an efficient LIB recycling system is established to handle the anticipated high volumes of retired EV batteries in the near future. The LIB waste stream consists of 25% of Battery electric vehicle (BEV), 36% long range plug in hybrid electric vehicle (PHEV) and 39% short range PHEV battery packs [106]. Although LIBs are dominant in today's EV batteries market, the reuse or second life of EV batteries concept is not limited to LIBs.

4.6.1 Feasibility study

Researchers at Sandia National Laboratory have studied the techno-economic viability of using second life NiMH EV batteries which have degraded to 30Wh/kg or 45Wh/kg and compared performance to new (first-life) LABs and advanced LABs. The study found the NiMH batteries performed at least as well as new LABs in stationary energy storage applications. In some instances, the used EV modules appeared capable of performing the same functions as new LABs over longer lifetimes. This study demonstrated reusing NiMH EV batteries in the secondary applications is technically feasible [107]. Figure 16 summarises the advantages of using the second life EV batteries.

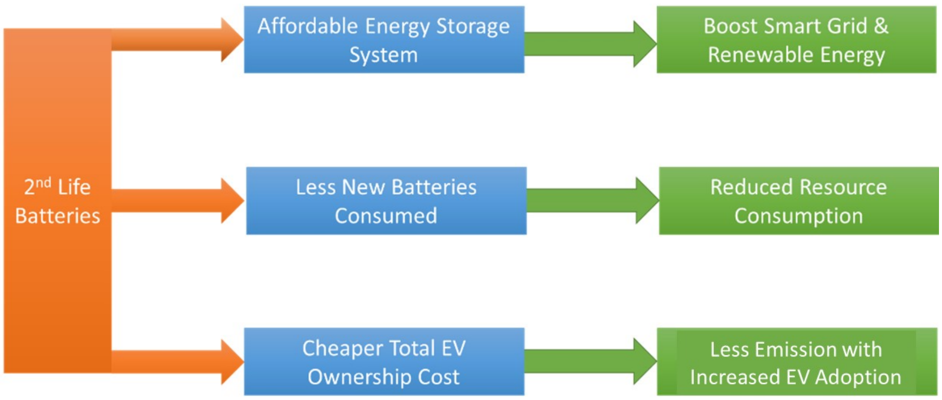


Figure 16 Summary of the primary advantages of using the second-life EV batteries.

4.6.2 Technical challenges

Heterogeneity between cell and modules

The retired EV batteries come with wide range of capabilities. Battery performance assessment is critical to predict how long and how well retired batteries would perform in second-life applications. The SLBs present larger cell to cell variability than the new batteries. The closer the match, the better the restored battery will perform and the longer the life will be. Packs designed for heavy loads and wide adverse temperature ranges are normally matched to ±2.5 percent. Such a tight tolerance may not be possible with refurbished cells and mono-blocks. Therefore, the heterogeneity between cells or modules is one of the major technical challenges of using SLBs. The current assessment of SLBs to determine if the used EV batteries are fit for the second life application involves visual inspection, verification of battery voltage followed by state of health assessment or capability test or others such as Quasi-OCV, EIS and OCV tests [108]. Cycling studies is commonly used where battery cells are charged and discharged under predefined conditions to observe the cell capacity, voltage, physical properties. After testing, batteries with similar characteristics are selected and grouped to form a homogenous second life battery pack.

Complex degradation phenomena

The other major technical challenge is the complex battery degradation phenomena. The LIBs ageing that leads to capacity fade is a combination of several ageing mechanisms with reactions specific to the particular materials and LIB chemistry. The two major factors on the degradation of negative electrode are solid electrolyte interphase (SEI) instability and lithium metal plating. The LIBs degradation mechanism can be broadly separated into three categories including loss of lithium inventory, loss of anode active material, loss of cathode active mass [109]. The challenge of truly understanding the battery failure mechanism is that it requires dismantling the cell and intensively inspecting individual components. For a LIB to operate in a reliable, efficient and safe manner, it requires a battery management system. The core function is to accurately estimate the State of Charge (SOC) and State of Health (SOH), which is challenging due to the lack of sensors for electrochemical phenomena inside the cells [110]. To evaluate the value of using a SLB, it is essential to understand the possible degradation of the SLB in terms of the capacity fade, impedance growth and efficiency fade as well as how long it can perform the second life task. However, the installation location and application use profile contribute significantly to its ageing. Aging mechanisms are different for each battery chemistry and use case. This makes modelling the ageing effect mathematically a complicated task [111]. Quick detection and assessment approaches are needed to achieve consistency and reduce the repurposing costs of SLBs. Battery management technology company Dukosi develops cell-level intelligence to optimise battery lifetime, monitoring and increasing the chance for second-life use. The company's cell management systems (CMS) records the battery usage data at the cell level so that at the end of their first life in EVs the CMS will provide a 'CV' of each battery cell thereby reducing or even avoiding the cost for testing second-life batteries [112]. Similarly, the control hardware developed by Relectrify to control individual cell performance in battery packs can also be utilised for second-life applications through individual cell control, thereby bypassing some of the issues of cell-to-cell tolerance requirements.

4.6.3 Economic study of battery second life

Second life batteries can be used in a wide range of applications such as residential, commercial and industrial applications. The residential and commercial use are regarded as small size energy application and the industrial ones usually are large application providing support to renewable energy sources such as wind, solar and transmission. The onsite energy storage in telecommunication energy management also brings opportunities to SLBs. The economic studies on various applications were reviewed and summarised by Martinez-Laserna et al. [74]. Based on this summary, applications according to their profitability are grouped and summarised with critical notes in Table 5. There are numerous applications tested and assessed as profitable such as distributed node telecom backup power, decentralised mini and microgrid, residential and light commercial load following, power backup for generation asset outages, residential demand management including energy time shift and peak shaving plus PV, smart grid load dispatch, UPS, voltage support, wind generation grid integration for short duration as well as T&D upgrade deferral. Three applications are concluded as not profitable which includes load levelling/energy load levelling, energy power reliability plus peak shaving and wind generation grid integration for long duration. Many other SLBs applications were marginal in their profitability by different studies, therefore these applications may or may not be profitable, such as area regulation, renewable capacity farming, renewable energy time-shift, transmission congestion relief and transmission support. It should be noted that new (first life battery systems) typically utilise multiple value streams for full economic benefits (e.g. peak shifting, FCAS and 6 second demand response). Although the aforementioned study did not probe this, it is likely that SLBs will also utilise multiple value streams for improving the economic benefits.

Table 5 Summary of economic analysis on the profitability of second life battery applications. Adapted from reference [74].

Applications	Profitable (Yes/Maybe/No)	Comments
Accelerated calendar life testing	Yes	Profitable
Decentralised mini and micro grid (electricity access in rural areas in emerging markets)	Yes	Profitable
Distributed node telecom backup power	Yes	Profitable
Electric service power quality	Yes	Limited profits agreed by several studies
Light commercial load following	Yes	Profitable
Load-levelling	Yes	Only profitable under most favourable conditions (reduced auxiliary fees or wide price differences between on-peak and off-peak periods)
Power backup for generation asset outages	Yes	Profitable, 1.5 year payback period
Residential demand management (Energy timeshift + peak shaving) +PV	Yes	Profitable concluded by different studies. Savings surplus the costs of the batteries; best case with 6 years payback period
Residential load following	Yes	Profitable
Smart grid load dispatch	Yes	Profitable, Utilities obtain profits from second life use and EV owners perceive a reduction on the LCOE of the batteries of about 20%
T&D upgrade deferral	Yes	Limited profits
UPS	Yes	Profitable
Voltage support	Yes	Limited profits or profitable concluded by different studies
Wind generation grid integration, Short duration	Yes	Limited profits agreed by several studies
Area regulation	Maybe	Limited profits
Area regulation + spinning reserve capacity	Maybe	Limited profits or not profitable from different studies
Demand charge management	Maybe	Limited profits or not profitable from different studies
Electric service reliability	Maybe	Limited profits or not profitable from different studies
Electric supply capacity	Maybe	Limited profits or not profitable from different studies
Electric supply reserve capacity	Maybe	Limited profits or not profitable from different studies
Energy time-shift	Maybe	Limited profits or not profitable from different studies
Load-following	Maybe	Limited profits or not profitable from different studies
Renewable capacity firming	Maybe	Limited profits or not profitable from different studies
Renewable energy time-shift	Maybe	Limited profits or not profitable from different studies
Substation on-site power	Maybe	Limited profits or not profitable from different studies
Time-of-use energy cost management	Maybe	Limited profits or not profitable from different studies
Transmission congestion relief	Maybe	Limited profits or not profitable from different studies
Transmission support	Maybe	Limited profits or not profitable from different studies
Load Levelling/Energy Load Levelling/Energy	No	Not profitable
Power reliability + peak shaving	No	Not profitable
Wind generation grid integration, long duration	No	Not profitable

Part V Australian battery waste policy

5.1 Waste LIBs transportation in Australia

Transportation of waste across Australia is a complex challenge for industry. There are currently 537 local government areas across the States and Territories and waste transportation and movement is regulated by the different Environmental Protection Agencies in each State or Territory. As a consequence, different regions in Australia have differing regulations regarding transportation, import and export of products (including wastes) and also differing fee structures. All of these can cause severe impediments to the transportation industry which in turn flows-through to the recycling industry, especially for companies which operate across multiple States and Territories and are serving a broad area for waste collection. The industry has been working with government agencies at both the State and Federal level to harmonise the differing regulations and fees. However, significant opportunities exist to enhance this work and rapidly deploy a harmonised Australian transportation policy for wastes including batteries.

New LIBs for either individual sale or within another product as well as waste lithium-ion batteries are listed in the Australian Code for the Transport of Dangerous Goods by Road & Rail as: Class 9 - miscellaneous dangerous substances and articles, including environmentally hazardous substances. Batteries must be packaged and transported in accordance with the Australian Dangerous Goods Code (ADG). As such, movement of batteries must be undertaken with appropriate regulatory approval and documentation. Batteries are subject to hazardous waste legal requirements which, depending on the jurisdiction, requires the supplier to: obtain an approved Consignment Authorisation issued by the destination State Environment Protection Authority prior to transportation; ensure that Waste Transport Certificates accompany the battery load in transit and be presented at the receiving facility upon delivery. Transport of dangerous goods also requires a dangerous goods transport document. The consignor must provide the dangerous goods transport document to the driver and ensure that it includes: Description of the dangerous goods e.g. UN Number, proper shipping name, class(es) and packing group, container type and number of containers and aggregate quantity. Finally the export of LIBs including waste LIBs also requires a permit from the Australian Government.

5.2 Battery stewardship scheme

The Australian Product Stewardship Act was established in 2011 which acknowledged the shared responsibility for managing wastes and their impact throughout the life cycle of a product. The Product Stewardship Act 2011 allows products to be regulated or product stewardship arrangements to be accredited by the Australian Government. The framework includes three forms of stewardship:

5.2.1 Voluntary stewardship

The voluntary industry-led and funded schemes enable products to be managed sustainably without the need for regulation. Industries can seek Australian Government voluntary product stewardship accreditation for their schemes. Accredited schemes are monitored to ensure they are achieving agreed outcomes.

5.2.2 Co-regulatory stewardship

Government sets the minimum outcomes and operational requirements, while industry develops and administers how those requirements and outcomes are achieved. Co-regulatory product stewardship schemes are a combination of industry action and Australian Government regulation.

5.2.3 Mandatory product stewardship

Mandatory product stewardship places a legal obligation on parties to take certain actions in relation to a product that leave little or no discretion on how the requirements are to be met. There are currently no fully mandatory product stewardship schemes in place under the Act.

Currently, the national television and computer recycling scheme (NTCRS) is under the co-regulatory stewardship. The day-to-day operation of the NTCRS is managed by four co-regulatory arrangements, Australian and New Zealand Recycling Platform (ANZRP), Ecycle Solutions (Ecycle), Electronics Product Stewardship Australasia (EPSA) and MRI PSO (MRI). The NTCRS has led to more than 360,000 tonnes of waste TV and computers being collected and recycled. From this collected waste more than 90% of reusable materials were recovered.

In 2016, the Department of Energy and Environment (DEE) included battery waste from other sources that were not included in the initial NTCRS in the approved product list of the Product Stewardship Act. In 2017, all batteries were included in the federal environment Minister's product list.

5.2.4 Battery Stewardship Scheme

In 2019, the Battery Stewardship Council submitted a "Proposed Stewardship scheme" for batteries which was approved in 2020 by the ACCC. The Stewardship scheme will charge a levy of up to 4 cents/EBU (24 grams) on battery imports. Upon end-of-life a rebate per kg for collection, sorting & processing will be offered to recyclers. Currently the proposed rebates are metro collections: $2.50, regional collections: $3.50, sorting $1.00/kg and processing $1.00/kg of battery waste.

A high level schematic of the Battery Stewardship Scheme is shown in Figure 17 [113]. The Scheme manages all aspects of the end-of-life requirements from management of membership, consumer education, governance and the industry participation and development. The main obligations of the scheme participants from the battery supply chain are listed in Figure 18 [113]. As can be seen, the scheme does not just target the end-of-life industry, but also requires participation by importers and retailers in the whole of life stewardship. Once implemented, the Battery Stewardship Scheme should become a driver for the recycling industry to expand and increase the current low collection and recycling rates.

It is anticipated that this scheme will assist the recycling industry through providing more certainty for investments. According to the Battery Stewardship Council, phase 2 of the scheme will be developed to include larger battery systems such as EVs and residential energy storage systems. In order to increase the success of this scheme it is crucial for more industry participants to become involved and proactive in scheme design and implementation phases.

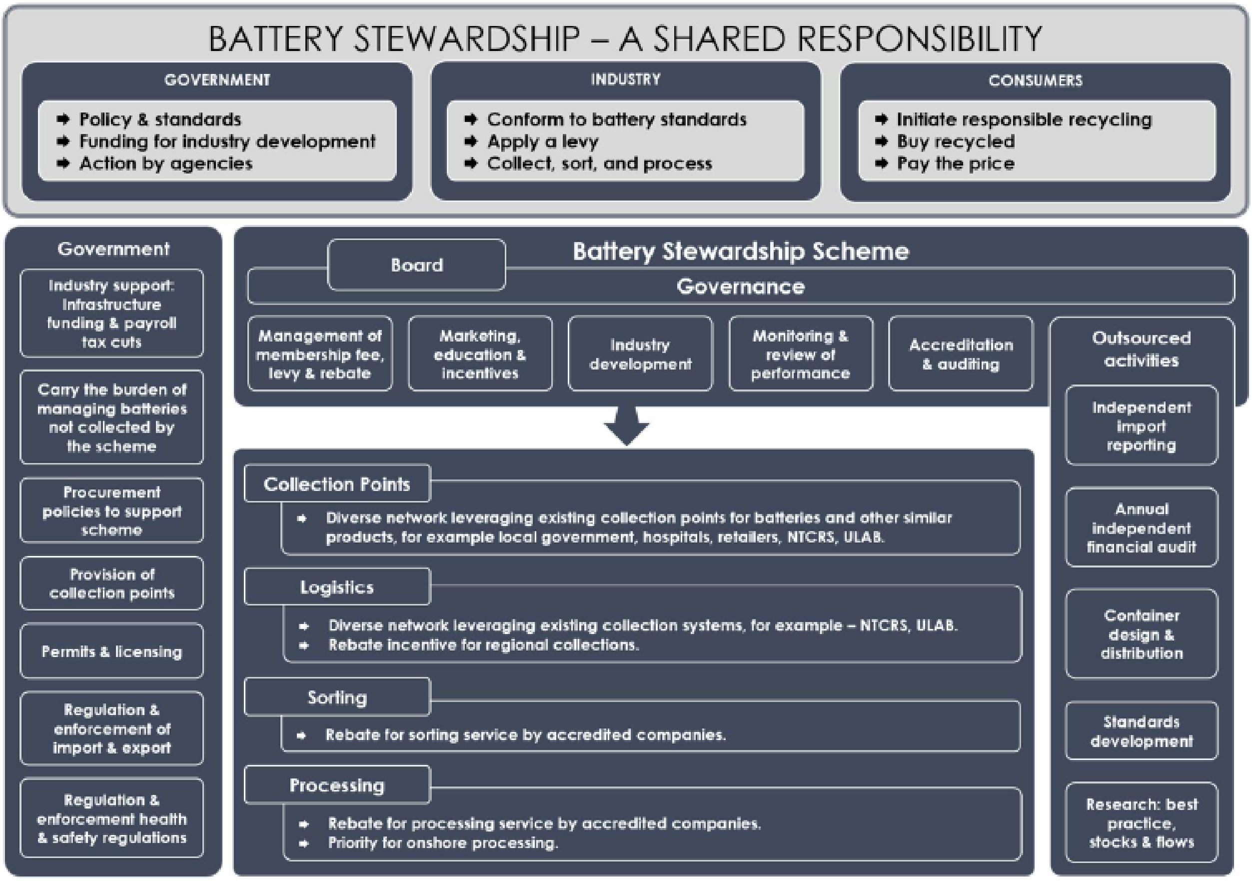


Figure 17 Overview of the Battery Stewardship Scheme (source Battery Stewardship Council) [113].

Figure 18 Obligations for different sectors under the Battery Stewardship Scheme [113].

5.3 Current national waste policy action plan

The regulations on waste battery treatment in general differ significantly between the States and Territories in Australia. Some jurisdictions still allow landfilling of LIB waste but others impose stricter recycling regulations. To date, the Australian Capital Territory was the first to ban e-waste landfill and made its recycling mandatory in 2005, followed by South Australia starting a landfill ban in 2010 and Victoria in 2019 [44,45,114]. This has created an immediate complex problem, since no waste management system was in place at the time of implementing new legislation combined with a lack of clear directions as to how various stakeholders are expected to address the impasse. In Australia, the development of policy and regulation in regard to deriving resource recovery from battery waste is developing. Battery waste, in particular LIBs, management was included in the national waste policy action plan of 2019:

> *"Action 3.2 Establish a Product Stewardship Investment Fund to accelerate work on new industry-led recycling schemes, including for batteries, electrical and electronic products, photovoltaic systems and plastic oil containers (led by Australian Government, act by 2020);*
>
> *Action 3.4 Preferred stewardship scheme for batteries (a) identified and (b) in place (led by Queensland Government, partnership with all governments, business sector and waste and resource recovery industry. By (a) 2020, (b)2022;*
>
> *Action 3.9 Develop a common approach to restrict the disposal of priority products and materials in landfill, starting with lithium-ion batteries, materials collected for the purpose of recycling, and e-waste."*

At the time of writing, as mentioned above, the industry led battery stewardship scheme is being implemented across Australia utilising support from the federal Government. In New South Wales, South Australia, Queensland and Victoria, State governments have announced financial support for growth of the recycling industry, including battery recycling as part of their COVID-19 economic recovery policies.

5.4 The recycling and waste reduction bill 2020

The Australia government has introduced landmark legislation into parliament in March 2020. The bill implements an export ban on waste plastic, paper, glass and tyres agreed upon by Commonwealth, State and Territory governments. This legislation also incorporates the Product Stewardship Act 2011 with improvements to encourage companies to take greater responsibility for the waste they generate. The bill memorandum pointed out that to support the delivery of strategies within the Action Plan, Ministers also agreed to strongly encourage major battery manufacturers, Energizer and Duracell, to participate in the new industry-led Battery Stewardship Scheme to improve the rate of battery recycling.

In addition to the federal level policies, the current government will commit $190 million to a new Recycling Modernisation Fund (RMF) that will generate $600 million of recycling investment and drive a billion-dollar transformation of Australia's waste and recycling capacity.

Part VI Battery recycling infrastructure in Australia

From collection to processing

6.1 Collection facilities

6.1.1 Household battery collections

Australian State and Territory governments clearly state in their websites that waste batteries should not be put in household general waste bin, green waste bin and recycle bins. The commonly used small size batteries both rechargeable and non-rechargeable including AA, AAA, C, D, 9Vs batteries, laptop batteries and mobile phone batteries can be dropped off in any of the permanent government designated drop off centres. Some States and councils provide household hazardous waste or chemical collection programs that take used batteries on scheduled dates. Apart from government funded drop off facilities, mobile phones batteries can be dropped off at participating retail stores or post waste batteries in a reply-paid envelope provided by MobileMuster program.

ALDI claims to be the first supermarket in Australia to offer a national battery collection program since 2013, which allowing shoppers to drop off any brand of used household batteries into battery recycling bin at the front of every ALDI store and other major retailers and supermarkets are following this action and deploying collection schemes. Currently, Officeworks, Battery World, IKEA, Bunnings Warehouse, Woolworths and Coles also offer free battery drop off services for small sized household batteries at participating stores. Eventually, these schemes should encompass all Australian States and Territories uniformly.

6.1.2 Commercial/car battery collections

As for commercial waste batteries, most car workshops, scrap metal dealers and service stations such as Supercheap Auto, Repco Auto parts and Battery World nationwide accept used car batteries for recycling. Figure 14 shows the national drop off locations offered by Battery World. Most of the drop off locations are along the coast in high density populated areas. Battery World also assist with the recycling or disposal of old mobile phones. Battery World may charge a fee to offset its recycling costs for batteries dropped off in commercial or bulk quantities.

Figure 19 Car battery drop off service from Battery World (https://www.batteryworld.com.au/).

The closest battery drop-off point for commercial batteries recycling in Australia can be found through Planet Ark's RecyclingNearYou website (https://recyclingnearyou.com.au/) and the Australian Battery Initiative (https://batteryrecycling.org.au/recycle-batteries/why/find-a-recycler/). The number of available commercial battery drop off locations and pickup businesses in Australia are shown in Table 6.

Table 6 Large battery drop off location and pickup business available in Australia.

States	Drop-off location	Pickup Business	Population%*	Population**	Drop-off /10^5 people
VIC	144	55	26.10	6,688,976	2.15
NSW	117	43	31.8	8,149,787	1.44
QLD	114	19	20.1	5,151,280	2.21
WA	75	26	10.4	2,665,339	2.81
SA	63	29	6.9	1,768,350	3.56
TAS	15	17	2.1	538,193	2.79
ACT	21	17	1.7	435,680	4.82
NT	8	14	1	256,283	3.12

*from Statista (https://www.statista.com/statistics/608819/australia-population-distribution-by-state/#:~:text=Population%20distribution%20Australia%202020%20by%20state&text=As%20of%20March%202020%2C%20The,states%20in%20terms%20of%20population.)
** Population on the 8th of December 2020.

6.1.3 Collection facilities in different States

Victoria

Permanent drop-off sites are typically located at council depots and transfer stations across Victoria. These permanent drop-off sites are for Victorian residential wastes only. Commercial battery recycling can be found from Australia Battery Recycling Initiative (ABRI) website where recycling companies are listed by location and battery type. Most mobile phone batteries are collected by the MobileMuster program, computer batteries are collected and recycled through Battery World, MRI e-cycle solution and SUEZ programs, and large batteries are collected via national network of battery recycling centres established by Century Yuasa and at many garages, transfer stations and waste management centres.

Some waste management companies run nationwide programs that recycle all types of batteries (except motor vehicle batteries). Flat-packed boxes are posted out to the required location and full boxes sent back for recycling with an administration fee.

New South Wales

Community Recycling Centres (CRCs) are permanent drop-off centres for common household wastes that can't be collected via council kerbside waste and recycling collection services. NSW householders can drop off problem wastes at these centres year-round, free of charge. Only household quantities of these materials will be accepted. As a guide, this is a maximum container of 20 litres or 20 kilograms for each waste type. The CRCs complement the Household Chemical CleanOut program. Businesses are not eligible to use Community Recycling Centres and should contact a waste disposal service directly or visit BusinessRecycling (https://businessrecycling.com.au/). Figure 20 maps the location of NSW current permanent household battery drop off community recycling centres. NSW EPA is also funding new and enhanced CRCs across NSW. Local councils and other organisations operate these centres in partnership with the EPA. Funding for the centres comes from the waste levy, as part of Waste Less, Recycle More scheme.

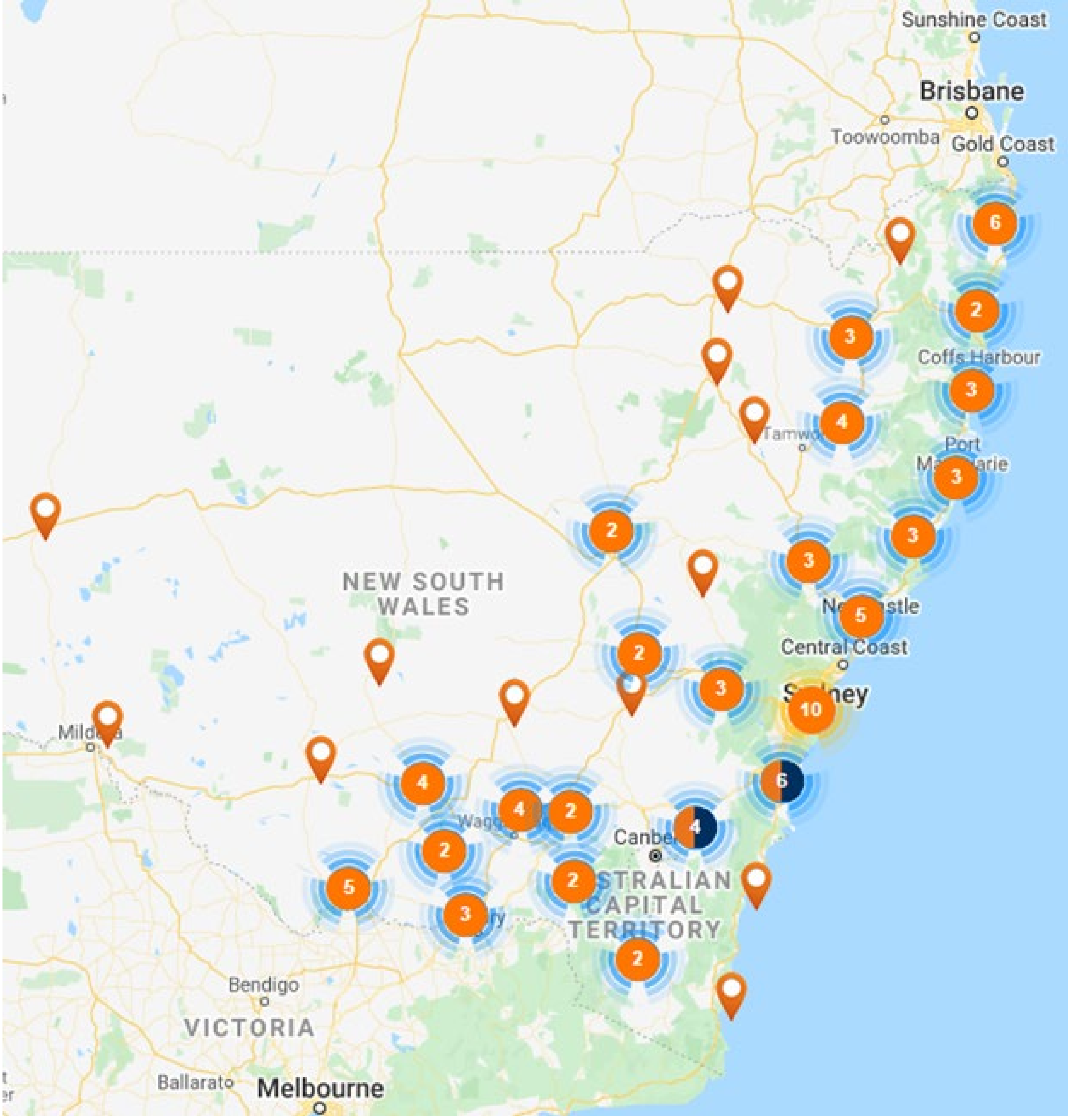


Figure 20 Map of battery drop of points in NSW Community Recycling Centres (https:/www.epa.nsw.gov.au/your-environment/recycling-and-reuse/household-recycling-overview/find-crcs-or-hcco)

Queensland

The Queensland government encourages residents to recycle waste batteries by dropping off at one of the resource recovery centres. They also advise on their website that rechargeable batteries cannot be placed in the general waste, recycling, or in the garden waste bins. In addition, they emphasise that placing single use batteries in recycling or garden waste bins would contaminate other recyclables or the mulch produced from garden waste.

Queensland claimed to have led the national effort to increase recycling and signalled the voluntary battery scheme to increase recycling rates (https://statements.qld.gov.au/statements/82094). The Queensland government wants to start with rechargeable batteries such as those found in power tools and other products like laptops and mobile phones as these are the ones that contain some of the harmful chemicals and are able to be more easily recycled. Similar to other states, the large size car batteries collection mostly relies on car workshops, scrap metal dealers and service stations. A collection network in QLD is mapped in Figure 21.

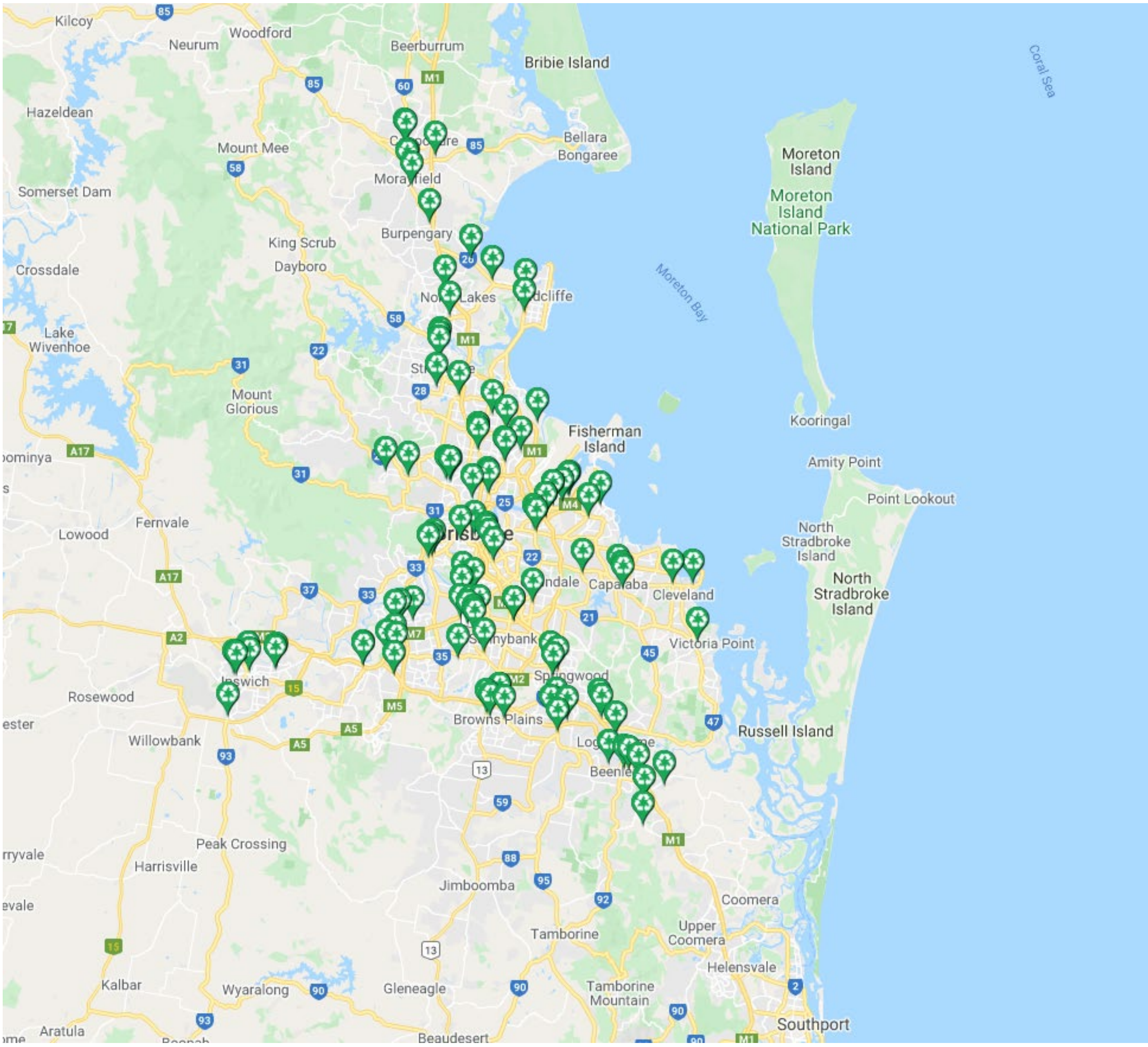


Figure 21 QLD industrial car battery collection network. https://recyclingnearyou.com.au/

South Australia

In South Australia batteries are collected through a range of retail organisations including ALDI, Bunnings, Ikea, Officeworks and Battery World in the Adelaide region. In addition, the South Australian EPA also state that car and truck batteries can be disposed of in the container deposit schemes. For commercial batteries (including rechargeable batteries consumers should contact their local waste disposal company. Dry cells and alkaline batteries can be disposed of in normal household rubbish bins. For rechargeable batteries such as mercury and lithium these can be disposed of in EPA hazardous household waste deposit sites. Consumers should contact their local council for further information for local drop-off points.

Australian Capital Territory

In the ACT batteries can be collected through a range of different drop-off locations. Many major retailers such as Battery World, Officeworks and ALDI will accept consumer batteries for recycling. Consumers can also order a “battery bucket” from MRI eCycle and can arrange collection once these are full. Furthermore batteries can be sent to resource recovery centres and further information can be found at: https://www.cityservices.act.gov.au/recyclopaedia/items/b/batteries-household.

Tasmania

In Tasmania batteries can be recycled through special drop-off points set up in many waste transfer stations and local council offices. These batteries are then collected by Toxfree for off shore shipping and materials recovery. A full list of drop-off locations can be found at the Rethink Waste website (https://rethinkwaste.com.au/household-battery-recycling/).

Northern Territory

Waste batteries can be sent for collection through Planet Ark. Consumers in the Darwin Council and Palmerston council regions can also contact the City of Darwin Council or Palmerston council (or view their websites) for further information. For all other consumers they can contact Planet Ark or the EPA for further information regarding drop off points.

Western Australia

In Western Australia a range of disposal options exist. Consumers can utilise multiple drop-off locations in places such as Battery World, Bunnings, local waste transfer depots and many local council drop off points. A full list of locations which can be searched for by consumer residence can be found at the recycleright website (https://recycleright.wa.gov.au/find-my-nearest/), where consumers can search for different waste types and find the nearest drop-off location to their location.

6.2 Recycling facilities

ABRI notes growth in the number recycling facilities in Australia over the last 2 years. In 2018 ABRI had 7 member companies providing waste battery collection and recycling services growing to 13 companies in 2020. We note that there are other companies who also provide these services but are not associated with ABRI.

A national network of Battery Recycling Centres has been established by Century Yuasa for environmentally responsible collection and recycling of used lead-acid batteries but currently a similar scheme is not available for LIB recycling. Table 4 summarise some of the current available LIB recycling facilities or technologies in Australia. Apart from the summarised companies, TES, Ecobatt, Ecocycle, RAMCAR, Supercharge Batteries and Enirgi Power Storage are also listed in ABRI as recyclers for LIBs in Australia. Although listed for LIB recycling, Enirgi power storage recycling’s major technology and process facility is for lead acid batteries located in a modern recycling plant in Wagga Wagga in NSW, however, as mentioned in the previous section, the recycling process technology is not suitable/transferable to LIB recycling. Total Green Recycling based in WA has expanded its e-waste and battery recycling service to LIBs in the recent years.

Table 7 LIB recycling facilities in Australia.

Company	Location	Capability
Envirostream Australia	VIC	Envirostream Australia collect waste LIBS, discharge, disassemble, granulate to produce black mass then exported the black mass to Korea for metal separation.
Neometals	WA	Neometals has been running lithium refinery in Australia for many years. In the past few years, it shifted its business away from lithium refinery to LIB recycling focusing on the European market where the spent LIB volume is expected to come. It has developed LIB recycling process technology, engaged with one of the largest German Engineering company SMS Group and built a recycling pilot plant in Canada to recycle all the Tesla's batteries. It has a 20,000 tonne commercial scale shredding plant. The technology/process can be readily applied to Australia if the volume of LIB in Australia rises in the future.
Lithium Australia	WA	Lithium Australia's battery recycling covers WA, QLD and VIC. It's battery recycling business include collection, sorting, crushing, separating crushed battery materials and battery metal separation. It has two lithium extraction processes (SiLeach® and LieNA®), cathode material production and battery recycling techniques. Its main business activities are extracting lithium from mine waste, covert to high spec cathode materials, and recycling spent LIBs and alkaline batteries via VSPC Ltd. Lithium Australia is also a battery cell/system manufacturer/supplier/retailer. A technology developer for the recovery of lithium chemicals from waste and fine spodumene and nanotechnology for the synthesis of lithium ferro phosphate cathode powders.
MRI eCycle	NSW, VIC, QLD, ACT	MRI eCycle recycle LAB as well as lithium batteries. Their process disassembles batteries from e-waste for recycling. They offer free collection and shipping including provision of "battery buckets" for residential and commercial consumers and also provision of e-waste bins for commercial waste collection.

Part VII Battery value chain stakeholder survey

Industry, government and researchers' perspectives

7.1 Survey methodology and stakeholder overview

To understand the status, challenges and future opportunities of LIB recycling and the future of LIB value chain development in Australia, 46 key stakeholders from 39 different organisations on the LIB value chain were invited to participate in this survey with a 62% response rate. The selected stakeholders are categorised into five groups. The survey covers a wide range of questions specifically designed for each stakeholder group. All responses have been de-identified to protect the privacy of participants. The five key stakeholder groups are:

- **Recycler group**: Battery recycling industry.
- **Manufacturer, importer or retailer group**: Battery chemicals supplier, battery manufacturer or battery retailer.
- **Policy and Regulatory group**: Battery waste management/policymaker at State level and government regulators.
- **Not for Profit Organisations group**: Not-for-profit Organisations consist of industry bodies.
- **Researcher group**: Research Organisations and Universities.

The operating areas of the invited stakeholders are shown in Figure 22a and the operational jurisdictions in Figure 22b.

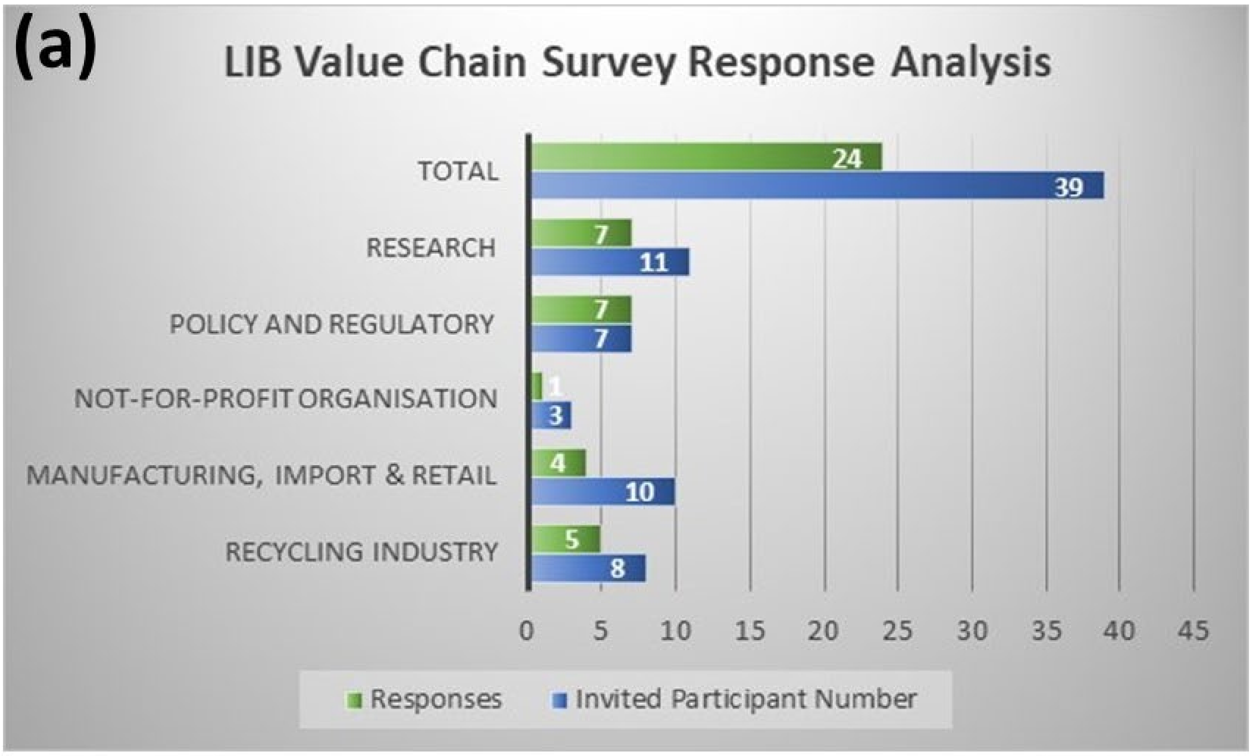


Figure 22 Mapping of survey responses on battery value chain in Australia. (a) Stakeholder response rate by group and (b) Stakeholder operational jurisdiction.

7.2 Views on LIB waste and recycling

Prior to engaging in the survey, baseline questions were asked of all participants to identify their views and understanding of the LIB battery waste and recycling industry status. Responses are summarised in Table 8 below.

Table 8 Stakeholder views on spent lithium-ion battery.

Question	Recycler	Manufacturer, import or retailer	Policy and regulatory	Not-for-profit organisation	Researchers	Total responses
LIBs are non-hazardous material and it is acceptable to place in landfill.	0%	0%	0%	0%	0%	0
LIBs are hazardous material and harmful to our environment and this waste stream should be managed outside of landfill sites.	19%	19%	5%	24%	33%	21
The economic value of the waste LIBs is low but the environmental impacts, if placed in landfill, is high.	25%	25%	0%	25%	25%	4
LIBs contain valuable critical materials which should be recovered through recycling.	18%	18%	5%	27%	32%	22
Recycling of waste LIBs presents an economic opportunity/business opportunity.	26%	21%	5%	16%	32%	19
The amount of waste LIBs is low now; disposal to landfill has nearly no impact. Management solutions should be considered when the quantity has increased.	0	0	0	0	0	0

Note: stakeholder group response percentage is calculated based on total responses for each row.

Of all the stakeholders interviewed, there is unanimous agreement that LIBs are a hazardous waste source which requires management and outside of landfill disposal.

Four stakeholders believe the economic value of the waste LIBs is low, but the environmental impact is high if placed in landfill. No stakeholder held the view that end-of-life management solutions should only be considered when the LIB waste quantity has increased.

Some of the stakeholders submitted comments on this topic and selected comments are presented below. There is agreement between recycling industry, manufacturing, importer and retail industry, not-for-profit sector and academia that landfilling of LIBs represents the loss of economic value and resources. The policy sector comments believe that the recycling industry should lead the resource recovery.

"I believe that the amount of waste LIBs from automotive provenance in landfills is extremely low, but solutions should urgently be defined as the numbers of end-of life EV batteries are expected to increase. It is possible that there are significant amounts of consumer (non-automotive) batteries in landfills. For these, collection is the main issue."

Industry stakeholder 1

"Batteries by definition would be classified in a number of jurisdictions as hazardous waste due to the nickel and cobalt in the cathode and also components of the electrolyte. The critical minerals in LIB, Ni, Co, Li, are resources that should be preserved, since at least in the short to medium term, there are limited new conventional sources that are economical exploitable. Technically cobalt is abundant, but deep-sea reserves etc. are still a research topic. There will be business opportunities around recycling, but it is difficult to tell how beneficial it will be for companies not already engaged in the value chain."

Industry stakeholder 2

"The pricing of all new material versus used materials ("waste") is a market failure. What we call "waste" is simply the arbitrary economic valuation we place during product lifecycles – while externalising costs to others at various stages. Emission is the most egregious example, but we don't price in overall environmental impacts, scarcity and range of other factors. There is also transfer of risk along the supply chain – the local government usually left with the costs involved even when their constituents might not have benefited – or not proportionally."

Industry stakeholder 3

"They are hazardous although a well-engineered landfill cell should be able to manage the hazards suitably (like other hazardous wastes disposed to landfills). However, the risk of fires in landfills from batteries is real and relevant."

Policy and regulatory stakeholder 1

"Recycling of LIBs would be best facilitated through a comprehensive, industry led national scheme."

Policy and regulatory stakeholder 2

"By putting the lithium-ion batteries into general landfill we are not only losing the opportunity to recover non-renewable resources, we are also losing the opportunity to reduce the environmental impacts of mining and manufacturing virgin materials."

Research stakeholder 1

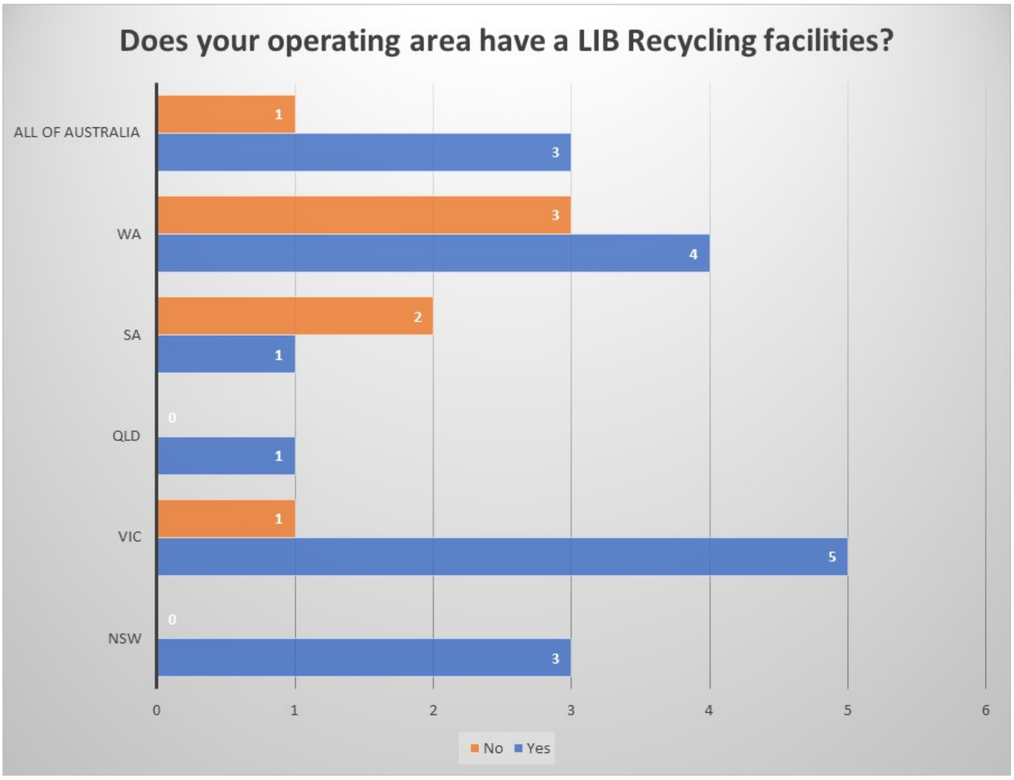
7.3 Public awareness of LIB recycling

81% of stakeholders believe the public awareness on LIB recycling in Australia is low. 18% of stakeholders believe the public awareness for small size household batteries is medium as there have been recent campaigns on battery recycling, battery drop off bins around libraries, shopping centres, supermarkets and local government buildings. Stakeholders who believe the public awareness is low pointed out that:

- High rate of inappropriate battery disposal; many people are still putting their batteries in the yellow top bins thinking they will be recycled by a materials recycling facility which costs Australia hundreds of millions of dollars per year in damage and repair. A “hot load” (fire in the back of a compactor truck) is a weekly occurrence for one jurisdiction. Councils across Australia are experiencing the same issue.
- Low rates of battery recycling demand.
- Householders find it difficult to identify the different battery technologies.
- Unaware of the possibility of recycling batteries.
- Carbon anode material within the LIB, albeit a major component is relative unknown.
- Battery recycling is emerging, but not entrenched as a mainstream practice; Large scale recycling has low optics, moreover it has an unclear pathway, at least within Australia for these large-scale batteries at end of life cycle (use).

We asked if stakeholders were aware of LIB recycling facilities and other battery chemistry recycling facilities in their operating area. The survey results are shown in Figure 23 a and b. The response shows discrepancies for the same operation area. Amongst the recycling industry, policy and regulatory sector and not-for profit organisations there is awareness of both LIB battery recycling facilities as well as the other chemistry types recycling. However, in the manufacturing, importer and retail and researchers’ sectors there is low awareness of existing facilities and recycling schemes. It can be concluded that the survey results indicate more public awareness promotion is needed across all sectors to promote existing recycling facilities and schemes.

(a)



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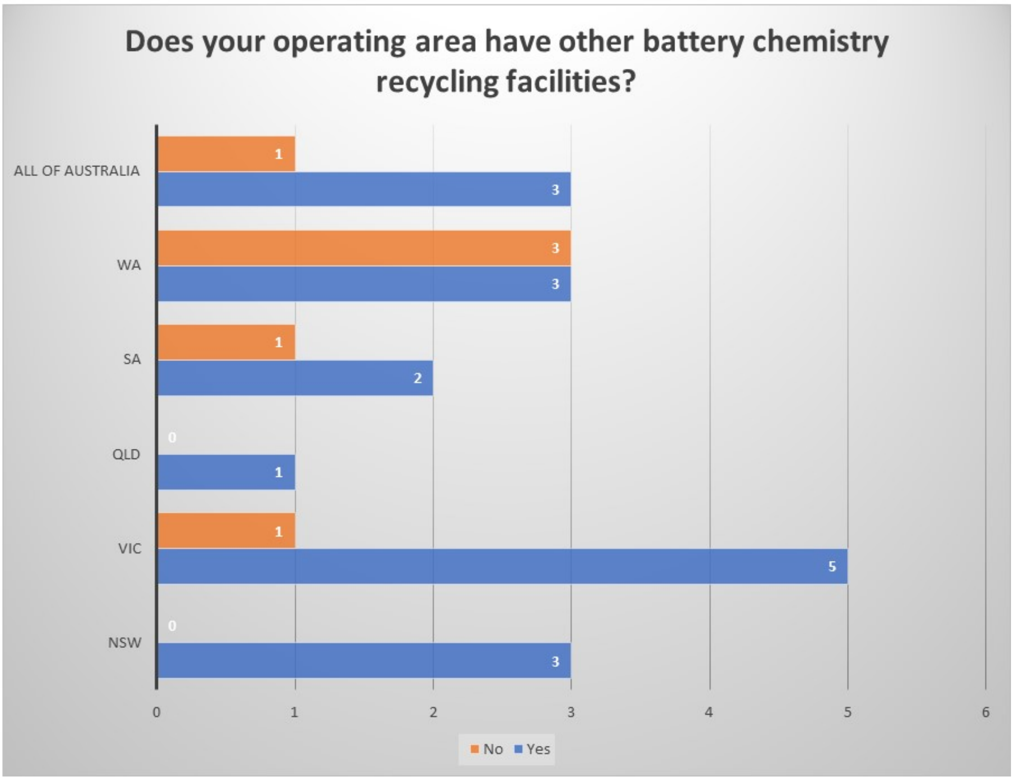


Figure 23 Stakeholder awareness of battery recycling facilities in Australia. (a) LIB Recycling facilities, (b) other battery chemistry types recycling facilities.

7.4 Future role of Australia in the global battery value chain

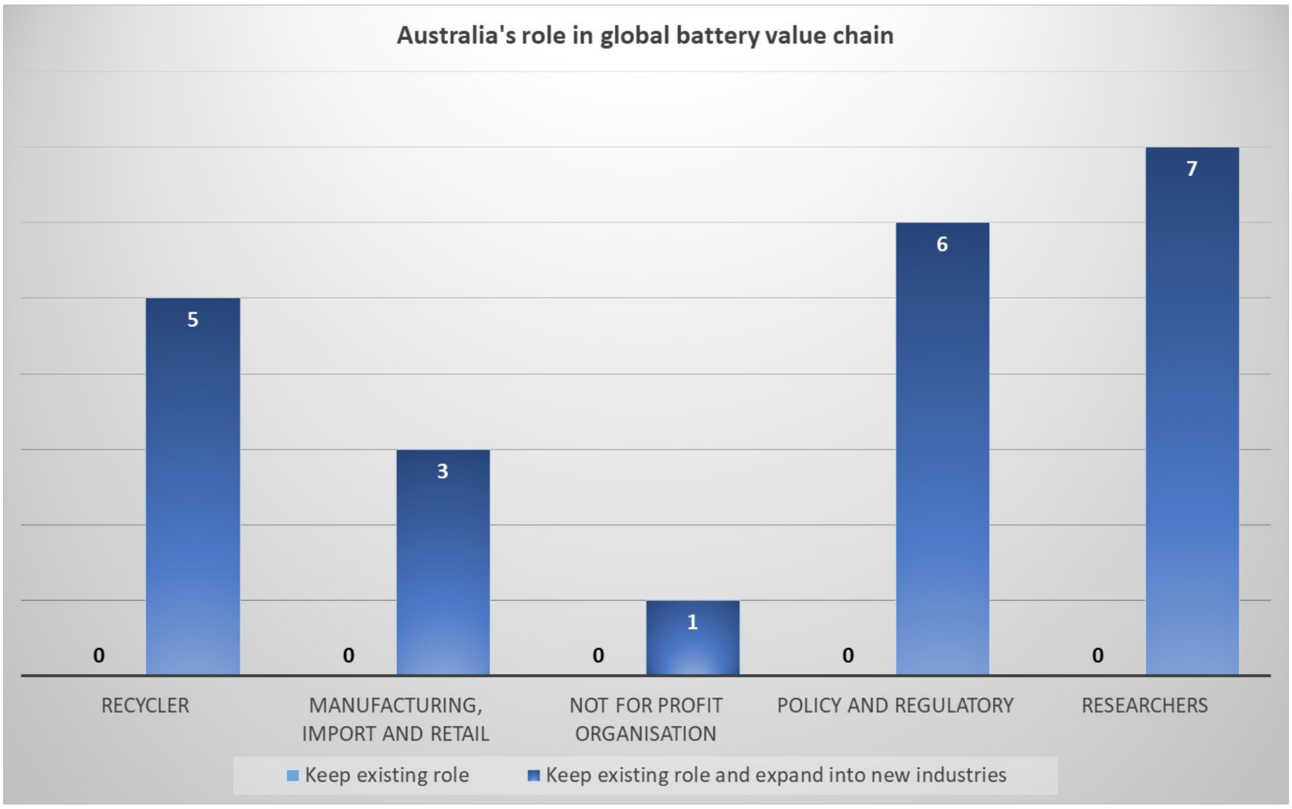


Figure 24 Views on Australia's current and future role in the battery value chain. [intro statement for this graph]

Figure 24 shows the responses received by each sector when asked on views around the future role of Australia in the global battery value chain. The highest proportion of responses were received from the recycling industry, policy and regulatory and research stakeholders. Australia is currently the largest global lithium resource exporter in the value chain. Stakeholders views were obtained to identify if Australia should keep to the existing role as a battery minerals supplier or strengthen the existing role and export as well as expand into new industries in this global battery value chain. Participants were also asked about the advantages and disadvantages of keep existing role or/and expanding into the new role to investigate what are the risks and opportunities for just being a resource exporter and expanding to new industries in the battery value chain. Comments of stakeholders are listed in Appendix (A.2). unanimously, all sectors stated that Australia should expand into new industries in the battery value chain, whilst keeping the existing industry.

Advantage of keep existing role

Some stakeholders believe that keeping the existing role is advantageous. The rationale is that it secures the existing market share and provides short term solutions to the emerging LIB waste problems and enables the requisite time for the industry to grow and develop. Additionally, as the waste streams grow, the existing operations and infrastructure can be leveraged. Other selected advantages of keeping existing roles as captured from stakeholder feedback are:

> *"All industry has moved to largely automated processes – that means the labour cost advantages of other countries has diminished and Australia's comparative advantage increases due to our more highly educated workforce and good social cohesion and stability. Building from nothing is much more difficult than building upon an existing base."*
>
> Not for profit stakeholder
>
> *"Export of waste would be less costly in the short term provided an international market exists. Noting this may not be a viable scenario if waste export is banned."*
>
> Policy and regulatory stakeholder
>
> *"Use limited government funding support available to secure the key industry where we dominate."*
>
> Research stakeholder

Disadvantage of keep existing role

The disadvantages pointed out by stakeholders are missed opportunities from strategic growth and expanding into the next stage of added value products, further entrenching current behaviours and supply chain models. The industry may not be well placed to take advantage of future policy changes. As not evolving with a changing world and being too heavily reliant on international markets, Australia would remain vulnerable to future shocks, commodity prices and international policy regimes if completely reliant on exporting waste LIBs. Other comments on the disadvantage of keeping existing role are:

> *"Loss of margin, loss of connectivity to customers, lost ethical sourcing and "green credential" opportunity and reduced value chain carbon emissions, lost opportunity for job creation."*
>
> Manufacturer, importer or retailer stakeholder
>
> *"Increased long term waste management costs, increased disposal to landfill and loss of resource. Reliance on international processors to manage/process waste."*
>
> Policy and regulatory stakeholder

One of the policy stakeholders mentioned our largest waste export destination, China has announced ban on all solid waste import, which is expected to come in force in January 2021.

Advantage of keep existing role and expand into new industries

The clear advantages of keeping the existing role commented by stakeholders are:

- Margin creation, significant value adding, developing downstream processing such as manufacturing industries
- Makes our markets more diverse and incentivises new opportunities around the whole supply chain; makes Australia more self-sufficient, less reliance on trading partners that like strongarm negotiating; reduces the risk in supply chain disruption to global OEM's with an alternative source of battery materials other than China

- Job creation, closer connectivity to customers, ethical sourcing and green credentials and reduced value chain carbon footprint, supports a circular economy
- Deliberate strategy to position Australia as primary metal supplier for the battery value chain
- Being well placed to take advantage of future policy changes, by creating a viable recycling industry, waste streams entering landfill can be avoided and resources recovered for reuse.

Other than the advantages listed above, some stakeholders also commented:

> *"Australia has huge clean energy resources, and massive metals & mineral resources. For all that we allow value adding to be done overseas and do little here. Worse, we extract very low fees for those resources (royalties, resource rent taxes) relative to other countries. For example, in 2017-18, LNG companies in Australia had revenue totalling $29.7 billion, yet paid just $1.07 billion in royalties levied under the petroleum resource rent tax (PRRT). Qatar, a close second behind Australia in production, received a staggering $26 billion in royalties. We do that with every resource – even wool, where we do not even clean it before export, a process that multiplies the value several times."*
>
> Recycling industry stakeholder
>
> *"Waste export bans and structural change in overseas markets (e.g. China ceasing all solid waste imports) means that expansion of domestic recycling & remanufacturing will be essential."*
>
> Policy and regulatory stakeholder

Disadvantage of keep existing role and expand into new industries

Most of participating stakeholders also commented regarding the disadvantages of expanding into new industries. The main risks and hurdles are:

- Requires substantial capital investment and development of markets in what is currently a competitive industry
- Complexity, lower rent downstream, risk of funding waste if mismanaged

> *"Most likely need a consortium of companies and federal level strategy. This will be a more difficult task than keeping the status quo."*
>
> Recycling industry stakeholder

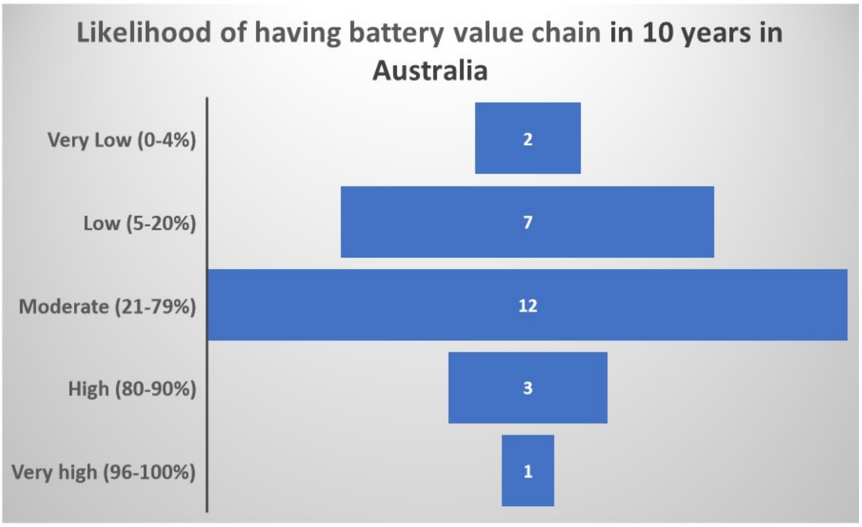
Overall, all sectors agree that Australia should maintain its existing resource production role, but also develop new industries to expand further into the battery value chain. The key barrier found for this was the requirement for high levels of upfront capital investment which would require industry consortiums or joint ventures supported by a national strategy to provide business confidence to invest.

7.5 Key barriers for future battery value chain in Australia

Stakeholders were asked their opinion if Australia should have its own battery value chain from mining of critical materials, battery manufacture, reuse to recycling and remanufacturing in 10 and 20 years. Figure 25 a and b summarise the views on the likelihood of battery value chain in Australia in 10 and 20 years.

The result revealed most of stakeholders believed the possibility of Australia having its own battery value chain in 10 years is low (5-20%) to moderate (21-79%) whereas in 20 years, the likelihood shifts to moderate (21-79%) to high (80-90%).The distribution of the votes from each group reveals that the perspective for the future battery value chain in Australia from our manufacture, import and retail and policy and regulatory sectors are more optimistic than research and recycling industry sectors.

(a)



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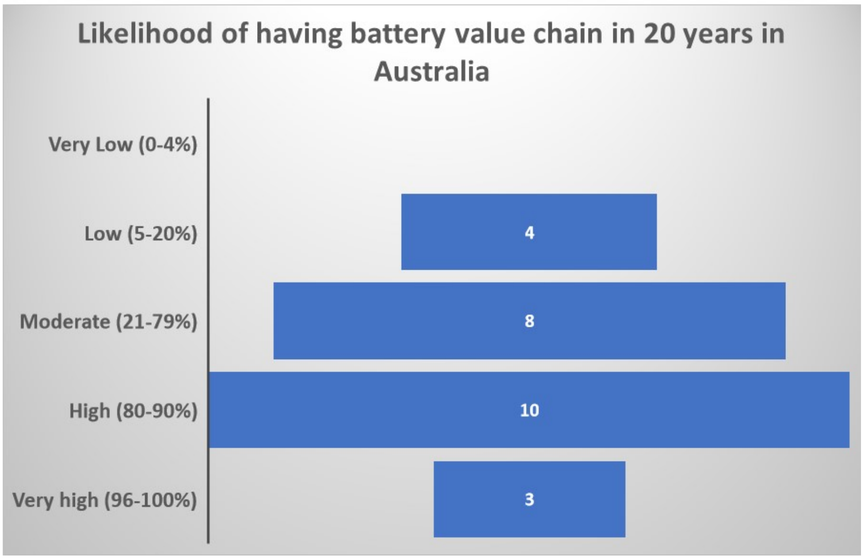


Figure 25 Likelihood of having battery value chain in Australia A) in 10 years, B) in 20 years.

To understand the reason of the stakeholder perspectives, we asked what the greatest barriers in the next 10 and 20 years along. The responses show that in the next 10 years, the greatest hurdle seen from our stakeholders includes

- Lack of investment
- Lack of government support in competing with overseas competitors and domestic regulation to ensure safe logistics for collection and storage
- Lack of processing infrastructure and recycling technology
- Lack of public engagement and industry participation
- Lack of a market

A summary of stakeholder views on the greatest barrier in the next 10 and 20 years in Australia is shown in Appendix A.1

An in-depth comment was received from one stakeholder:

What do you think the greatest hurdle/barrier is in the next 10 years? (e.g. mining, manufacturing, reuse, recycling, regulatory etc.)

"1. Lack of nationalistic interest – China, Indonesia, Germany and other nations are treating LIB as the next space race. There is no doubt that the value chain needs to be economically independent in the future. However, national interests will ensure establishment of the value chain in particular countries in the next few years. While Australia has the resources, it is difficult for multi-nationals to ignore the incentives being offered elsewhere.

2. Market hype – LIB is a value-add opportunity. However, it is not a golden goose. Automotive markets are large, but profits are small. VW strategic margin 2025 is 7-8% before special items (one-time expense or source of income that a company does not expect to recur in future years). https://www.volkswagen-newsroom.com/en/press-releases/volkswagen-confirms-strategic-financial-targets-of-together-2025-5579. Australia can have a whole new industry with many jobs, but over hyped metal prices will cause a few bad cases that deter future investment. It needs to be a clear realisation that the ICE cost parity target of 100 USD/kWh will not increase to cover higher profits from mining companies."

What do you think the greatest hurdle/barrier is in the next 20 years? (e.g. mining, manufacturing, reuse, recycling, regulatory etc.)

"1. Refilling the holes – while we can value add, there is still a net loss of resources from Australia and a lot of empty holes long term. Australia needs to figure out how to have the metal resources return so the industry is sustainable for the next 100 years, not just 20 years. This is where recycling, minerals tracing and digitalisation have a great potential. People are focused on where the minerals are coming from, however, there is equal value in being able to identify metal that has left Australia and being able to bring it back into the country via recycling.

2. Federal support & long-term federal level strategy – the Australian government is supportive of mining, but it tends to be a short to mid-term view. There needs to be a 25+ year view as well that ensures there is a transition from selling minerals to a service of processing minerals / waste batteries many times over. Without a long-term view Australia will struggle *to compete. For example, China was encouraging companies to go to the DRC in early 2000s to secure cobalt resource – Hauyou Cobalt is a perfect example.*

3. Reliance on Debt Financing – While the model works there needs to be better sources of funding to establish the battery industry. Smaller and med size market participants are needed to create a sustainable market. Debt financing is often difficult for smaller players which will push the industry towards a few larger companies. Also, debt financing encourages taking the decisions that generate cash flow fast (selling concentrate), opposed to value adding (more CAPEX, less uncertain future).

4. Metal price risk management – currently only Ni metal has liquidity (LME) that enables futures options to manage price risk. Li, Co need to have liquid markets. In addition, recovered material compositions applicable to the battery market, sulphate, spent batteries metals (black mass) also need liquid markets and willing participants."

7.6 Opportunities in the battery value chain

7.6.1 Current vs. future opportunities

Areas of opportunity along the battery value chain were summarised and presented to stakeholders for them to vote what are current and future (in the next 20 years) opportunities in Australia. Votes from all groups are summed and plotted in Figure 26. The horizonal value represents the number of votes from stakeholders. The voting results show that most stakeholders believe currently mining of battery materials, battery recycling and materials recovery, and battery materials manufacture are the top three opportunities. Over the next 20 years, the top three opportunities remain, whereas battery cell manufacturing and battery refurbishment/ remanufacture are emerging opportunities.

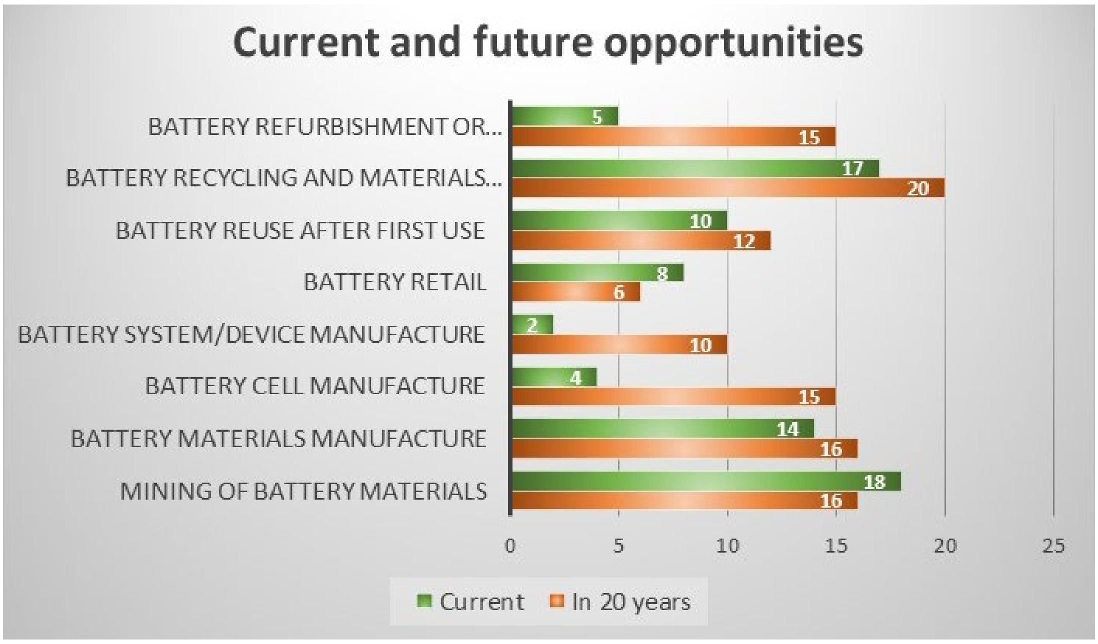


Figure 26 Views on current opportunities and opportunities in the Australian battery value chain over the next 20 years.

7.6.2 Stakeholder views on areas of opportunities

Comparing votes from different stakeholder groups (Figure 27), it's not surprising that recyclers vote battery recycling and materials recycling as current opportunities. Among the current top three voted opportunities, the survey shows all policy and regulatory stakeholders believe battery recycling and material recovery is the current opportunity. Most of the recycling industry and research stakeholders think battery materials manufacture and mining of battery materials are the current opportunities. Except the top three voted current opportunities, some recycling industry stakeholder and most of research stakeholders think battery reuse after first use is also an important opportunity.

Overall, all sectors believe there are strong opportunities for future Australian industries, namely second-life, recycling and materials recovery and cell manufacturing as the top opportunities identified.

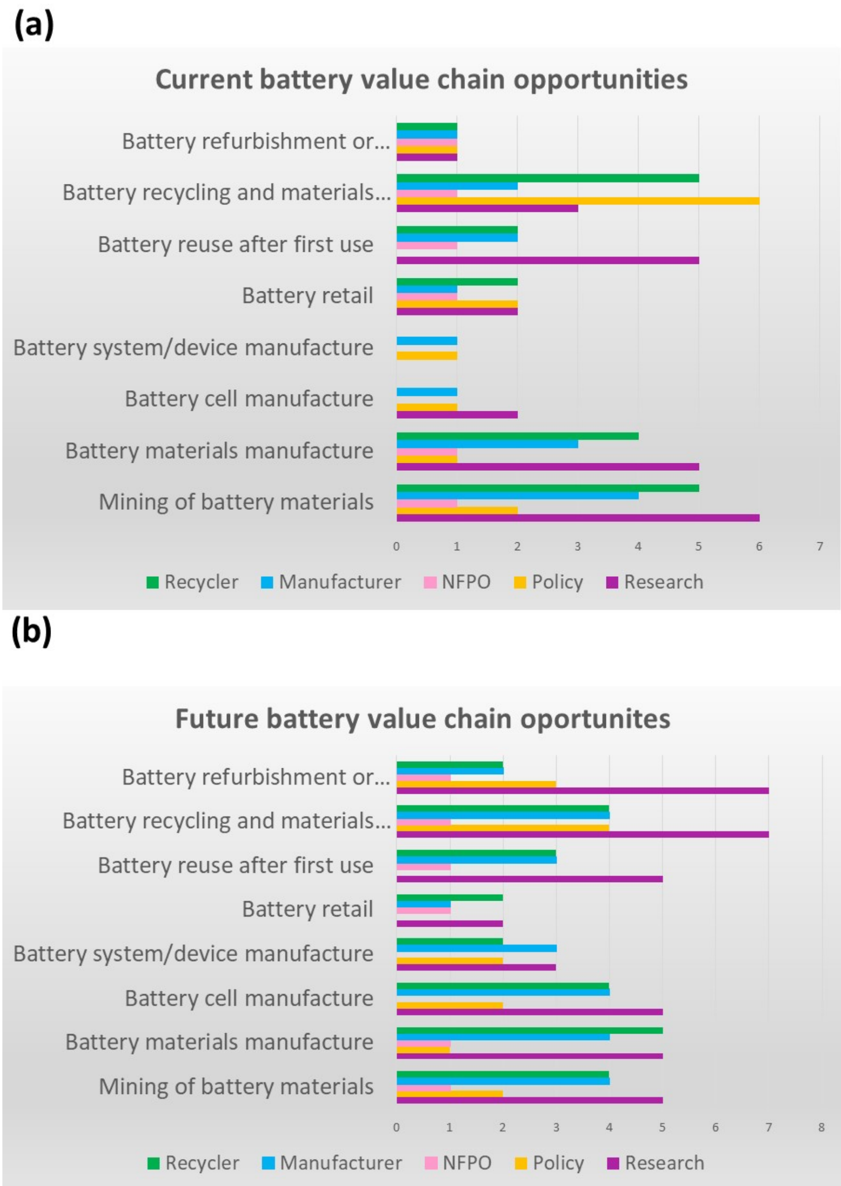


Figure 27 Views by stakeholder groups on (a) current opportunities and (b) future opportunities in the next 20 years for Australia in the battery value chain.

7.7 Specific challenges in battery recycling industry

This section discusses gaps and challenges present in the LIB recycling industry as well as exploring possible improvements and captures views from stakeholders on potential solutions.

7.7.1 Challenges in waste collection and transportation

Stakeholders responded on the status of the waste battery infrastructure in Australia (Figure 28). The majority of participants across all the stakeholder groups think the current infrastructure needs to be improved to meet the current and future needs. A quarter responded that current infrastructure is sufficient to deal with current volume but not enough for the future volume.

Stakeholder views on the challenges of battery waste collection were identified as:

- Cost: Lack of economic driver to collect, cost of collecting, cost of complying with Australian Dangerous Goods Code & Controlled Waste Regulations, Australian geographical spread and population density.
- Infrastructure: Lack of collection infrastructure, the collection system needs to improve and be refined, no efficient collection method, more convenient neighbourhood drop-off locations needed.
- Policy: No set standards or policy; no laws around custodianship of the battery, no packing guidelines, lack of policy supporting recycling of batteries, who is responsible for collection yet to be defined, high cost and complicated and confusing policies and regulations, lack of consumer incentive to recycle, lack of long term educational and engagement programs.
- Volume: Lack of non-Lead acid batteries, low public awareness lead to low collection rate. Additionally, a lack of drop-off options and infrastructure, as well as the costs of collection hinder the volumes being collected for recycling.
- Risk of fire: Lack of education on where batteries should be disposed, there is no easy, clear way to identify LIBs from different chemistry batteries, contamination of other battery waste stream lead to fire incidents.

One of the stakeholders commented there needs to be a co-ordinated approach on the whole waste stream accompanied by a public communications strategy. We note that the Federal Government has taken a pro-active approach in stewardship schemes including the battery stewardship scheme and has assisted the Battery Stewardship Council with advice and support to ensure the scheme was setup and deployed in Australia.

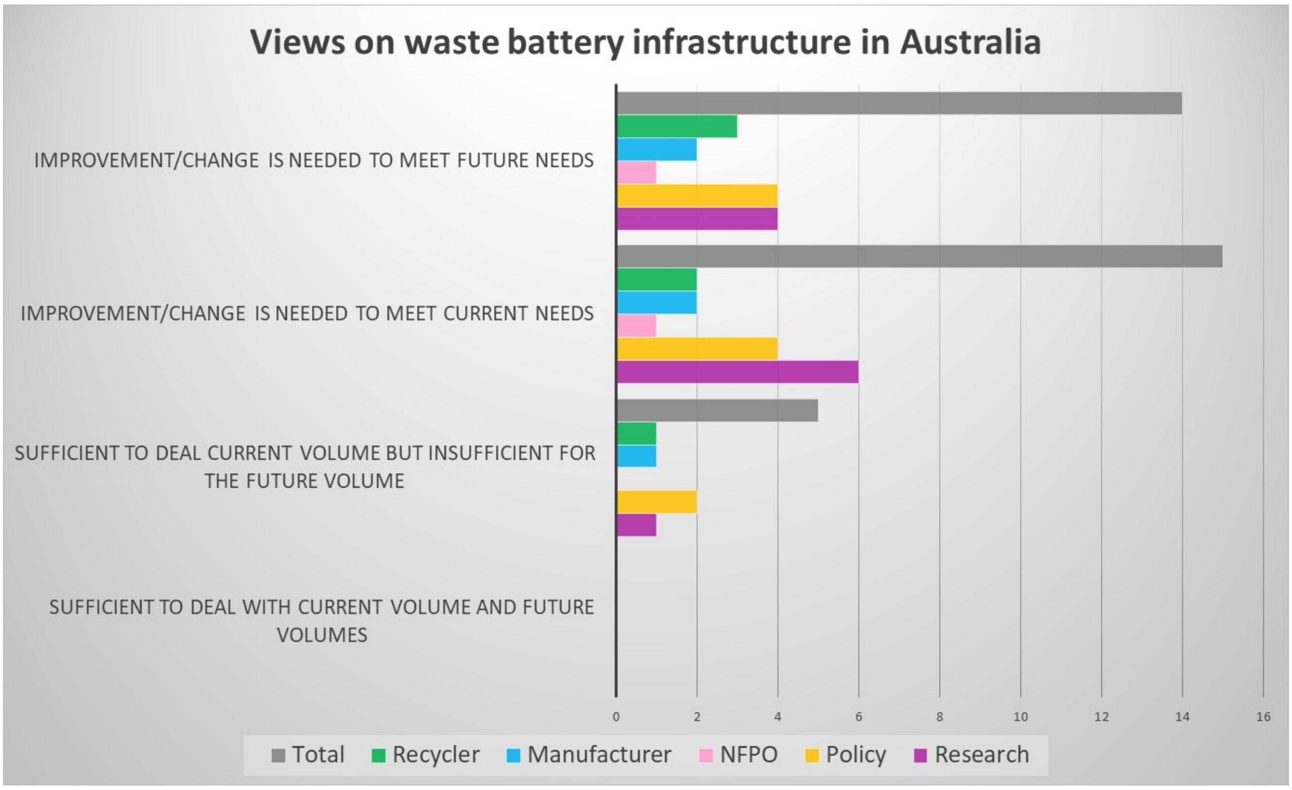


Figure 28 Stakeholder view on the current battery infrastructure in Australia.

Unified transportation regulations vs current regulations

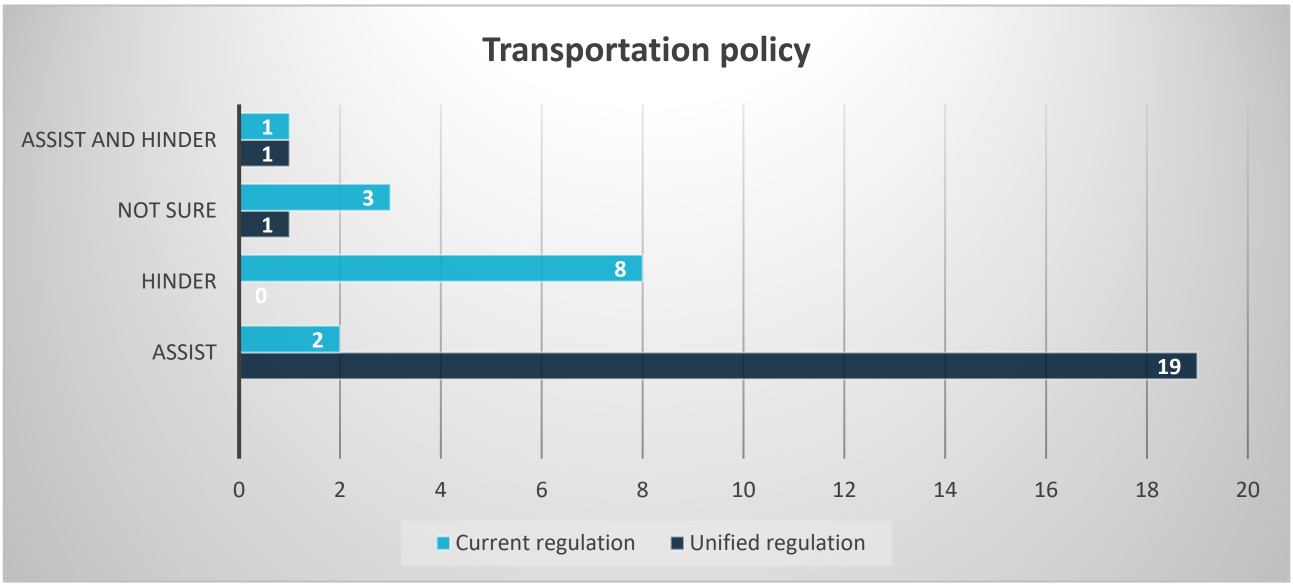


Figure 29 Views on current and unified transportation policy.

Participants were asked their views and perspectives of current waste battery transportation policies and views on a possible unified transportation policy across the nation. Eight stakeholders stated that the current transportation policy hinders the recycling industry. It is noted nearly all the hinder votes on current transportation regulation are from recycling industry stakeholders. One stakeholder left the following comment:

> *"Both assist and hinder, they control risks which assists the transport as it reduces the likelihood of catastrophe, but they can be burdensome resulting in people not following the protocol and this can create a price arbitrage encouraging behaviour that goes against the regulations."*

On views of a unified transportation policy, a greater response rate was observed and all sectors unanimously have a perspective that a unified national transportation policy will assist the battery recycling industry.

What technology, facility/equipment, policy could be helpful to improve the transportation process

One of the recyclers commented discharging technique for LIB will be very helpful as the risks fall away significantly once a LIB is discharged. Another industry stakeholder pointed out the chemistry information and state of health (SoH) could be helpful. For recycling purposes, SoH information is not needed but for second-life or repurposing, SoH information is significant. Other comments include RFID on items and barcode/QR code tracking register, first and foremost national legislation to ensure consistency across states – similar to other waste issues, online waste tracking certificates. A stakeholder from the research group commented:

> *"Australia has the resources, logistics and capability to recycle their own lithium-ion batteries at many locations, with major drivers being land availability; proximity to ports and related export infrastructure; labour; energy; and water. None of these are commercial barriers in Australia if Australia takes the opportunity to implement small scale recycling technologies for waste battery recycling locally, even in the rural and remote places."*

Centralised versus decentralised recycling system

To address the cost of collection and transportation, and investigate whether it is economically viable to have a centralised processing point for LIB recycling or have a decentralised LIB recycling processing points, we asked about whether it is economical viable to transfer waste across multiple Australian jurisdictions, one stakeholder pointed out the collection & transport to processing centres is complex logistically involving high costs. Australia has a population of 25 million people, in a nation three-quarters the geographical size of China which has a population of 1.4 billion, hence the market has to be export. Stakeholders from recycling industry sector believe that:

> *"The economic viability is a null point; it will just cost more from one state to another which would make it economically viable. It's better to have multiple processing points in different jurisdictions when the volume can support the capital outlay required to set up a processing point, this is in line with environmental best practice of minimising emissions and it will also reduce the transport risk of moving waste batteries."*
>
> Recycler stakeholder 1

“Have de-energisation / shredding / mechanical separation locally, centralised refining capacity possible. Safe to transport when in shredded state.”

Recycler stakeholder 2

“Mixed system - centralised for some jurisdictions and decentralised for others.”

Recycler stakeholder 3

“ Developing a near-source LiB de-energisation / shredding / mechanical separation system Australia-wide, and sending the black powder and mixed copper/aluminum to specialty refiners in Australia.”

Recycler stakeholder 4

“EOL batteries are costly to transport. Given the large distances to consider in Australia, the first priority should be converting spent batteries to black mass, which is easier and more economical to transport. Subsequent transformation from black mass to advanced battery grade materials, precursors, active materials, cells and packs will be driven by volume. Reuse may have some opportunity in certain cases (not expected to make sense for a majority of spent batteries), and should be explored in parallel with recycling. The main challenges for repurposing are not technical but rather economics -based, and any successful strategy will need to define a solid business model.”

Manufacturing, importer and retailer stakeholder

How to improve the collection system and increase collection rate

Recycling industry sector perspective

The stakeholders from recycling industry sector think that regulation changes and incentives are extremely important such as implementation of Battery Stewardship Scheme. Additionally, policy changes at a State Government level to promote end of life batteries recycling, guidelines and policies that ensure batteries are collected and stored at licensed and certified businesses to control the risks are also needed. When asked about the current Australian battery recycling permit system, two stakeholders from recycling industry responded and both believe the permit system can be improved but is usable at present. One of the recyclers commented:

“Lack of policy around what is allowed in the waste and recycling bin. There is no real consequence for a resident when they put something in their bin, this needs to change.”

Policy and regulatory sector perspective

The policy and regulatory sector stakeholders agree that product stewardship is important for batteries throughout their whole life cycle and collection systems need to be expanded to provide battery consumers easily accessible drop off points that appropriately manage environmental and human health risks associated with battery drop off.

Researchers sector perspective

Suggestions from the research stakeholders include extended producer responsibility – make the original equipment manufacturers responsible for the lifecycle of the battery, place a deposit on batteries, barcode labelling and conduct more recycling research. It was also pointed out that government should have clear guidelines, regulations, policies and incentives for the manufacturers, consumers, recyclers and industry peak bodies and researchers for collection, separation and recycling safely.

Importance rating of factors

Stakeholders voted on the importance of the four factors that affect the collection rate including incentive, public awareness, collection infrastructure and regulation. The survey results reveal that collection infrastructure, public awareness and regulation are equally extremely important, followed by incentives being important according to total votes from all groups.

Technical challenges of using automated collection facility like glass/can/plastic bottle collection program

Some participants believe there are no technical challenges as batteries are currently recycled in EU countries. There was significant concern about fire risks and chemical reactions if leaking or damaged batteries are mixed with other battery chemistries. Others believed batteries should never be taken anywhere but recycling companies. It worth noting that this type of facility is currently used for recycling of small format batteries from consumer electronics. Therefore, as EV and energy storage systems come offline these will provide an increase in processing volume for these facilities. A government stakeholder mentioned there are programs in NSW to encourage the adoption of renewables and electric vehicles (details can be found on https://www.environment.nsw.gov.au/topics/climate-change/net-zero-plan; https://www.ess.nsw.gov.au/Home; https://energysaver.nsw.gov.au/households/solar-and-battery-power).

"Container deposit schemes use compliant barcodes on containers that can be read by automated collection points to facilitate a refund, which incentivises the return of the container. This required little manufacturing change as containers already had a barcode on them.

Batteries generally do not have barcodes on them (the barcode is on the packaging the battery comes in which is disposed of before the battery is used. Changes to battery manufacturing processes (which generally occur overseas) to include a code directly on the battery is likely to be challenging and expensive for manufacturers. An effective automated approach to identifying battery types and chemistries is a challenge automated battery collection would need to overcome."

Business impact of import and export ban on waste battery

80% of stakeholders from the recycling industry sector responded to this question. Two of the recyclers believe there would be no effect on their business. One reported significant positive impact from an export ban to increase the potential volume of end of life batteries and there is no impact from banning waste battery import in short term, however, it would prevent the opportunity to expand the business of providing a second life to imported batteries. Another recycler suggested the business would be able to identify new opportunities in the battery recycling value chain as a consequence of an export limitation or ban, such as refining of end of life NMC/NCA cathode material, the recycler also reported no impact from import battery waste ban. One of the policy and regulatory stakeholders pointed out that the solid waste import ban in China, which is one of the largest waste battery export destinations is expected to come in force shortly from January 2021. When asked if in the future Australia were to ban battery waste export how would State Governments manage waste streams, the policy and regulatory stakeholder responded:

> *"Market led solutions supported by policy and regulations."*
>
> *"In the short term, there is a risk of further stockpiling and most batteries will likely be transported interstate."*
>
> *"Commonwealth involvement would be in the policy legislative development space. Regulation would be in the context of Commonwealth legislation."*

7.7.2 Challenges in waste battery storage

How the waste battery stockpiling is managed in Australia

The survey reveals that battery stockpiling is regulated at a States and Territory level. The EPA manages waste storage through environment protection licenses with conditions outlining quantities etc. to ensure that incidents are minimised. Under the current Environment Protection Act 1970, facilities which process over 500 tonnes/year of specified e-waste (including rechargeable batteries) are required to obtain a licence. The current policy framework addresses risk of harm to environment from fire in stockpiled materials and sets out key management requirements for facilities which store combustible materials. One stakeholder commented Australia has some guidelines for the storage and several incentives for waste battery storage system, but there is still more to be achieved in this area.

The primary challenge of waste battery storage

The main challenges associated with LIB storage from the majority of responses is safety (the risk of fire and explosion) which has massive impact on the industry and society. Policy and regulatory stakeholders commented that the risk of fire is from inappropriate storage & management of end-of-life batteries. They are aware of the issues with the stockpiling of LIBs and other batteries at commercial recycling facilities. These batteries are sometimes stored in a manner that increases the risk of fire or other negative events for instance, where batteries are stored uncovered (e.g. wooden boxes that are exposed to the weather). Government waste management agencies manage both actual and perceived fire risks. It was also pointed out by government stakeholders that limited processing capacity has led to stockpiling of LIBs and other batteries. Stockpiling has health, safety and environmental risks and these risks are sometimes realised when feedstock input exceeds processing capacity. It was also suggested by stakeholders that if there is a battery waste tracking system, the stockpiling issue could be eliminated. There is a clear opportunity to improve enforcement procedures and communications with other agencies such as fire brigades to manage fire and safety risks.

Cost of battery recycling business insurance

Recycling industry stakeholders stated that the cost of business insurance is either very high or hard to get due to the LIB fire risks in every step of recovering batteries (from the drop off at public locations by the consumer, to the storage and waste facilities, to transporting to intermediary locations, to transport over east, to shredding at processing). One of the recyclers commented that it has become more difficult to get insurance due to spate of recent battery related fires. Another recycler claimed that Australian insurers are refusing to insure anyone under the ANZSIC code 2922 for building insurance.

Other challenges in waste storage

Other gaps identified by recycler stakeholders were unsuitable, non-compliant vessels used for storage, lack of subject specific standards, lack of guidelines, lack of risk mitigation infrastructure and lack of discharging protocols. Additionally, stakeholders also pointed out that there was still a lack of access to waste products and in some instances the cost of access to the waste for processing was prohibitive. However, this can be mitigated through increasing collection networks and infrastructure. Some stakeholders also pointed out:

> *"All regulations need supporting compliance regimes – storage & transport of recycled materials are no different. Few areas offer strong compliance, electrical safety is probably the best, but it tends to be overly prescriptive and as so often varies between jurisdictions."*
>
> Not for profit organisation stakeholder
>
> *"Controlled waste regulations are in many instances a duplication of the DG regulations and vary from state to state."*
>
> Recycler stakeholder

7.7.3 Challenges in waste LIB recycling process (sorting, separation, markets etc.)

The challenges after collection were identified as:

- sorting difficulties
- capacity for disassembly
- achieving high purity recovered material
- high cost of entry due to high capital investment
- markets for recovered material.

Sorting, disassembly and high purity requirement

The sorting difficulty is a consequence of the lack of an appropriate labelling/barcode system which makes it hard to identify battery chemistry. On top of the labelling issue, the physical appearance of LIBs on the market at this stage varies and makes it hard to apply automation and is therefore labour intensive. The LIBs should be designed in a way that is easy to be dissembled and refurbished without compromising operational safety.

When asked whether labelling of LIBs has any technical barriers, such as to make it durable and recognisable, research stakeholders commented that there is no technical issue to achieve the desired outcome. If the battery waste labelling is in place, the waste tracking would then become viable, which will be beneficial for many areas/stages of the recycling industry as well as battery waste management.

Stakeholders from the manufacturing, importers and retail group responded that technically to get high purity recycled material is no longer a challenge, however cost of achieving high purity recycled material (metal compounds) is challenging.

> *"Ideally, economics will drive supply chain circularity. An economic driver based on the intrinsic value of the batteries (which also requires efficient recycling processes and logistics) will encourage collection. This is a critical first step in the longer-term circular supply chain goal."*

One recycler commented at present recycling 18650's for the steel casing only is more cost effective than recovering all the materials and suggested:

> *"This could be done through tariffs or taxes giving recycled battery materials an advantage over batteries produced with virgin materials. The challenge will be verifying the product make up and quantifying the percentage of recycled material in the battery."*

Cost of entry

The metal separation processes involve large capital and the process is usually complex. There is high upfront cost to invest in the plant process and is seen by several stakeholders as one of the major barriers. The uncertainty of the market and associated risks make it hard for business to make such a huge investment. In other industries, economic modelling tools are beneficial for decision making on complex investments. When asked if economic tools would be beneficial for the recycling industry, most respondents were unsure and unaware of availability of any such tools. One recycling industry stakeholder disclosed that they have developed internal models for LIB manufacturing and greenhouse gas emissions but still require further data for accurate modelling. When asked about what sort of techno-economic modelling tool features would help their business or future investments in the battery value chain, most of participants responded as not sure. It was not surprising to see some of the industry stakeholders respond that incentives and funding for a plant will motivate them to move into downstream processing and metals separation. Below is another thought about developing downstream metal recycling process from one of the stakeholders:

> *"Who owns the metal? Recycling can be a service; customer is charged a waste treatment charge by the recycler with a guarantee on the metal return rate. Alternatively, the recycler is buying the scrap. Buying the scrap will involve a lot of working capital when the total volumes of metal are considered. OEMs and other sellers of the scrap battery metals will want significant payables."*

Views on where recovered materials can be utilised

The main barrier of keeping the recycled metal compound in the battery value chain is the purity of the recovered material and the cost of recycling compared to the virgin mined material. It was suggested by one stakeholder that new markets for the recycled materials from the waste battery should be created which is not necessarily in the energy industry, it could be other industries as well. However, most of stakeholders across different groups expressed the same view that recycled materials should go to the highest possible value applications with lowest impact on the environment. Low value applications are viable options for recovered materials in the short term until the technology develops and it becomes feasible to move material into higher value applications.

In addition, from the policy and regulatory stakeholder sectors perspective, using battery materials in low value/quality product should not be encouraged, since the benefits of adding heavy metal compounds to cement is dubious and in their view, dilution of waste in other products should not be a solution.

Some research stakeholders suggested the recycled material should be used for any purpose where required, the chemical elements within are chemical elements so indestructible and potentially recyclable infinite number of times. If technology enables recovery in more advanced usable forms then this would be a benefit, such as sensor application, supercapacitors and battery applications.

The manufacturing stakeholders commented many recycling products are already ultrapure, thereby lending themselves to reintroduction into the supply chain as far downstream as possible. The blending of critical raw battery materials with recovered battery materials is the best pathway for success. However, Australia does not currently have downstream processing/manufacturing capability.

7.7.4 Challenges in spent LIB reuse

For reuse of waste LIB materials to make new products, the main challenges identified are the price of the recycled material compare to the virgin material, the purity and customer acceptance. When asked about the important characteristics of recycled material, the manufacturing, importers and retail stakeholders, revealed costs, quality and purity are the top two characteristics, followed by transportation and supply chains as shown in Figure 30.

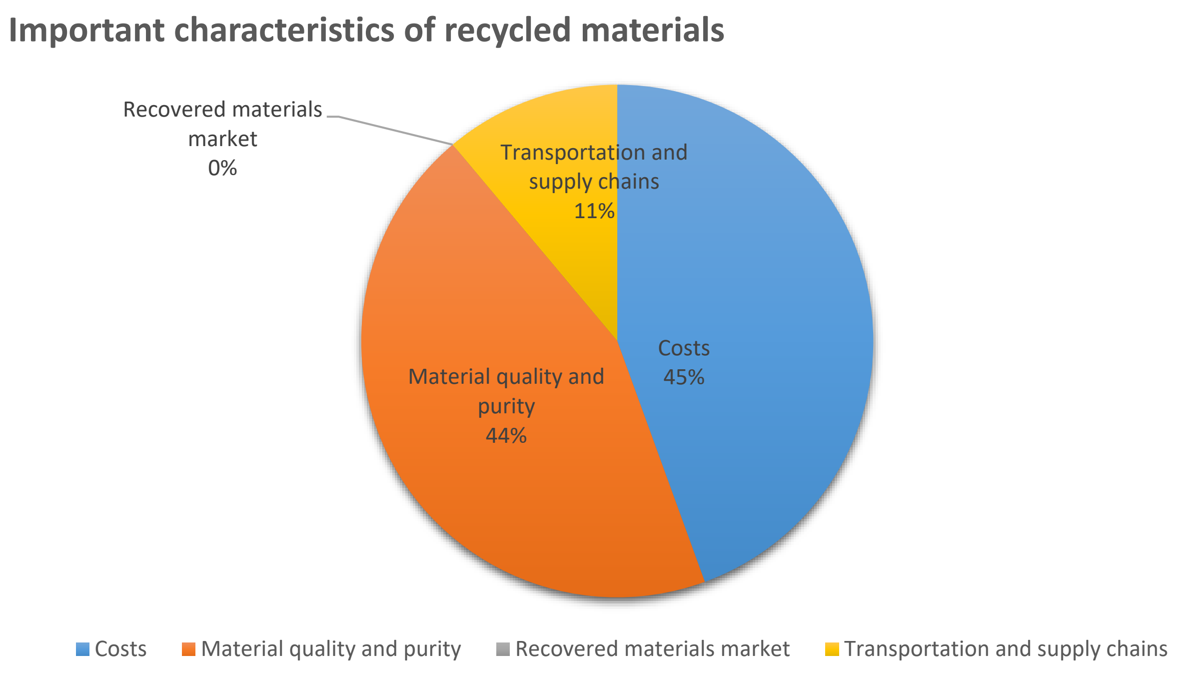


Figure 30 Views on the important characteristics of recycled material for LIB manufacturing industry.

Customer acceptance factors for refurbished batteries

This survey also investigated the importance of key barriers preventing business entering the battery second-life industry. Fifteen stakeholders across all the five groups discussed the customer acceptance factors (Figure 31). In these stakeholders views, price of second-life battery systems would be the key customer acceptance issue. This would then be followed by the suitability of the units for the application. The survey results also revealed that brand reputation is a key risk that stakeholders are concerned about. Six participants stated that other issues would be needed to resolved for customer acceptance of second-life batteries, in their opinion. These other factors are warranty, safety, reliability/durability, availability and public awareness in regard to the viable options. Amongst all participants safety is included in majority of the comments.

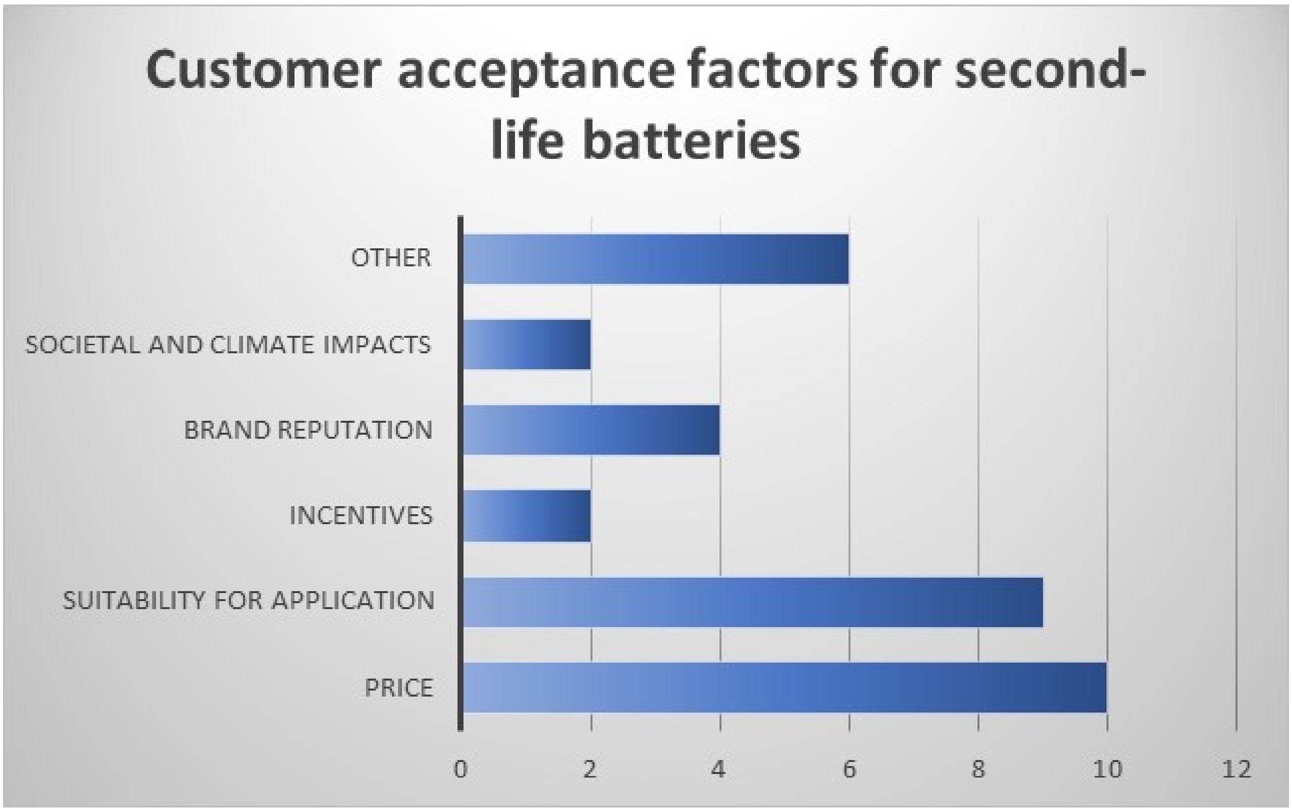


Figure 31 Views on second-life LIB customer acceptance affecters.

Barriers for battery second life industry

Two stakeholders, one each from the recycler group and the research group said they have plans to refurbish batteries, one stakeholder has already been refurbishing batteries on a small scale. All the remaining participating stakeholder groups responded either no or don't know or not applicable. The key barriers reported by industry stakeholders are:

> *"Money & inclination."*
>
> *"Cost and lack of steady, reliable supply of EOL batteries."*

One stakeholder pointed out:

> *"We deal with end of life batteries in very large volumes. We would not be able to assess if any of them were viable for refurbishment. So, identifying these is the biggest barrier as well as who would do this and how this would be done."*

It was also commented by researchers that:

> *"Lack of a solid business case is the key barriers to develop this new industry. The market changes very quickly, without government regulation in place, it is very risky. If there is government regulation, it is more likely to have a robust business."*

What support is needed for business to transition into this emerging area

The survey shows an Australian second-life industry will require:

- affordable/competitive consumer prices
- relevant and clear information for consumers
- funding for pilot plant and manufacturing setup
- incentives to refurbish batteries

Supporting methods from government or recycling and reuse industries

A majority of policy and regulatory stakeholders responded to what methods can be used develop battery recycling industry or grow existing battery recycling industry. The responses are presented below:

> *"Support for the development of a new / expanded infrastructure, technology and increasing the volume of battery feedstock are likely to be the most effective responses."*
>
> *"Product stewardship."*
>
> *"Scalable demonstration plants, rebates for batteries recycled/recovered."*
>
> *"E-waste ban, ensuring all feedstock availability for batteries. Further funding for transport, collection and product stewardship needs to be provided at a national level in order to cover the true cost of battery management."*

When asked if there are any impediments to second life battery use for stationary power the response was that environmental safety requirements around disposal and operation would need to be met.

Impact of LIB recycling/reuse on manufacturing/ retailing industry

The responses from industry stakeholders revealed, in their view, that the growth of battery recycling and materials industry in Australia would have major to significant positive impacts on manufacturing, importers and retail industry and positive impacts on the recycling industry. All of the responding industry stakeholders claim they can transition to utilise recovered materials from recycled batteries with two reporting they are currently utilising recovered materials from recycled batteries among which one is at final funding stage for project construction.

Biggest business / policy barriers for battery reuse/recycling

Several stakeholders shared the same views that the emerging sectors are not well addressed by current regulation, the current environmental regulation is fragmented and differs by State. The volume of waste LIBs are quite low and the cost associated with recycling these batteries are high which make the collection and transport for recycling uneconomical. To make the recycling a success a minimum volume must be collected and available to justify the capital required to operate a battery recycling facility. Keeping batteries out of landfill and economic incentives would assist with this.

An industry stakeholder pointed out that a lack of enforcement of policy is another big business barrier as it gives advantages to unethical processes that are less costly but less effective at achieving good outcomes; the characteristic of batteries (low weight and volume), drop off points must be widespread and convenient, and overcoming the mentality that " it's just too easy for someone to throw batteries into their waste bin". Clear communication with penalties to help educate the public that batteries are not allowed to be put in their waste and recycling bins is required, in their view.

Our policy and regulatory stakeholders commented:

> *"Producer responsibility – lack of regulation for this, not any local markets for manufacturing/reprocessing batteries, or not enough recovered materials to support manufacturing."*
>
> *"Regulatory, Product Stewardship to mandate recycling collection points across Australia."*
>
> *"Strong commitment to participate (and bear associated costs) by battery manufacturers and importers."*
>
> *"There needs to be policy / regulatory incentives to reuse and recycle else we'll continue doing what we do."*

From our researcher stakeholders:

> *"Size of market, lack of accountability now for custodianship."*
>
> *"Manufacturers are only concerned to lower the costs and increase battery longevity and charge capacity and are not paying attention on the recyclability and no clear pathways, technologies, guidelines, regulations have been developed to reduce, reuse and recycle the LIBs in large-scale and small-scale economical recycling. Cost of recycling by using the current recycling methods is the main barrier."*

7.8 Actions

The participating stakeholders were asked what actions, in their views, would help alleviate the problems in battery recycling industry. The suggestions are grouped into policy and regulation, technical solutions and consumer awareness/collection to address the biggest gaps identified.

7.8.1 Stakeholder suggested policy and regulation actions

Stakeholders noted that the world's second largest battery market, Europe is tightening policies on using hazardous materials is to encourage a circular economy. These policy changes will affect the design of devices such as phones, laptops and other portable gadgets as devices without removable batteries are set to be prohibited (https://www.pv-magazine.com/2020/12/10/european-commission-proposes-minimum-sustainability-thresholds-for-batteries/). Some of these European changes could be adopted for Australian application.

- Creating end of life battery specific regulations for transport and storage. No one solution can service all, therefore region-specific guidelines could be supplementary to national battery waste regulation in a way that should, facilitate, not impose extra burdens. Allocate resources to enforce the regulations to ensure the guidelines in the standard are implemented and used. Clear policies on the recycling and recovery of materials versus landfilling. Define who needs to collect the batteries. A long-term strategy would also be very useful.

- Battery deposit return schemes can be expanded, drop off network to provide more convenience to recycle plus incentives for collection and subsidies for processing of recycled materials. Mandating recycling of batteries (e.g. return to the store to purchase new ones at discounted price) and recycling domestically. Funding support for established recycling business should be provided.
- Taxing batteries made from virgin materials and providing rebates to batteries made from recycled materials; providing tax breaks for companies to make battery grade materials in Australia.
- Better insurance options (no property owner wants waste batteries stored in their facility due to the high cost in premiums for building insurance).
- Developing a battery recycling standard including transport, storage and recycling. CSIRO notes that AS/NZS 5377:2013 has been published for the collection, storage, transport and treatment of end-of-life electrical and electronic equipment. The Standard includes specific requirements for management of batteries recovered with e-waste, where batteries need to be removed as an 'identifiable stream' before the equipment is processed. However, no specific battery recycling Standard exists in the Australia/New Zealand region. At the time of writing this report, AS/NZS 5377:2013 was currently undergoing a major review and update. It can be expected that some of the gaps identified above may be addressed during this review and updating process.
- Regulatory standards for battery imports to be at a specific safety standard, include lithium containing batteries to all have a standard colouring (for easy segregation at Local Government level).

Comments and suggestions from several policy and regulatory stakeholders:

"Currently, the Australian Government has supported industry led action on batteries both through its recycling agenda and direct support to the Australian Battery Stewardship Council (BSC). The Commonwealth has supported BSC in securing key industry participation and, in conjunction with State and Territory governments, has provided significant financial support to support the work of the BSC. Continued Government support to voluntary industry-led action with a credible threat of regulation, in the absence of voluntary action, are important government / policy responses."

"A well designed national mandatory product stewardship scheme for handheld batteries is urgently needed, similar to the Paint back scheme design where an ACCC levy is approved to add a value at point of sale to support the product stewardship scheme. I understand this is in process currently."

"Battery product stewardship – producer responsibility. Have manufacturers consider end of life in their design. Regulatory standards for battery imports to be at a specific safety standard, include lithium containing batteries to all have a standard colouring (for easy segregation at Local Government level)."

7.8.2 Technical solutions needed

Our recycling industry stakeholders noted there are numerous promising technical solutions to battery recycling. The best solutions will offer solid business models to extract maximum intrinsic value from the batteries that will drive collection and will also have high recovery efficiencies, keeping critical battery materials in the supply chain. A policy and regulatory stakeholder commented that more cost-effective technical solutions for recycling would support the domestic industry, increase domestic recycling and refurbishment capacity.

Areas that need technical solutions were identified as:

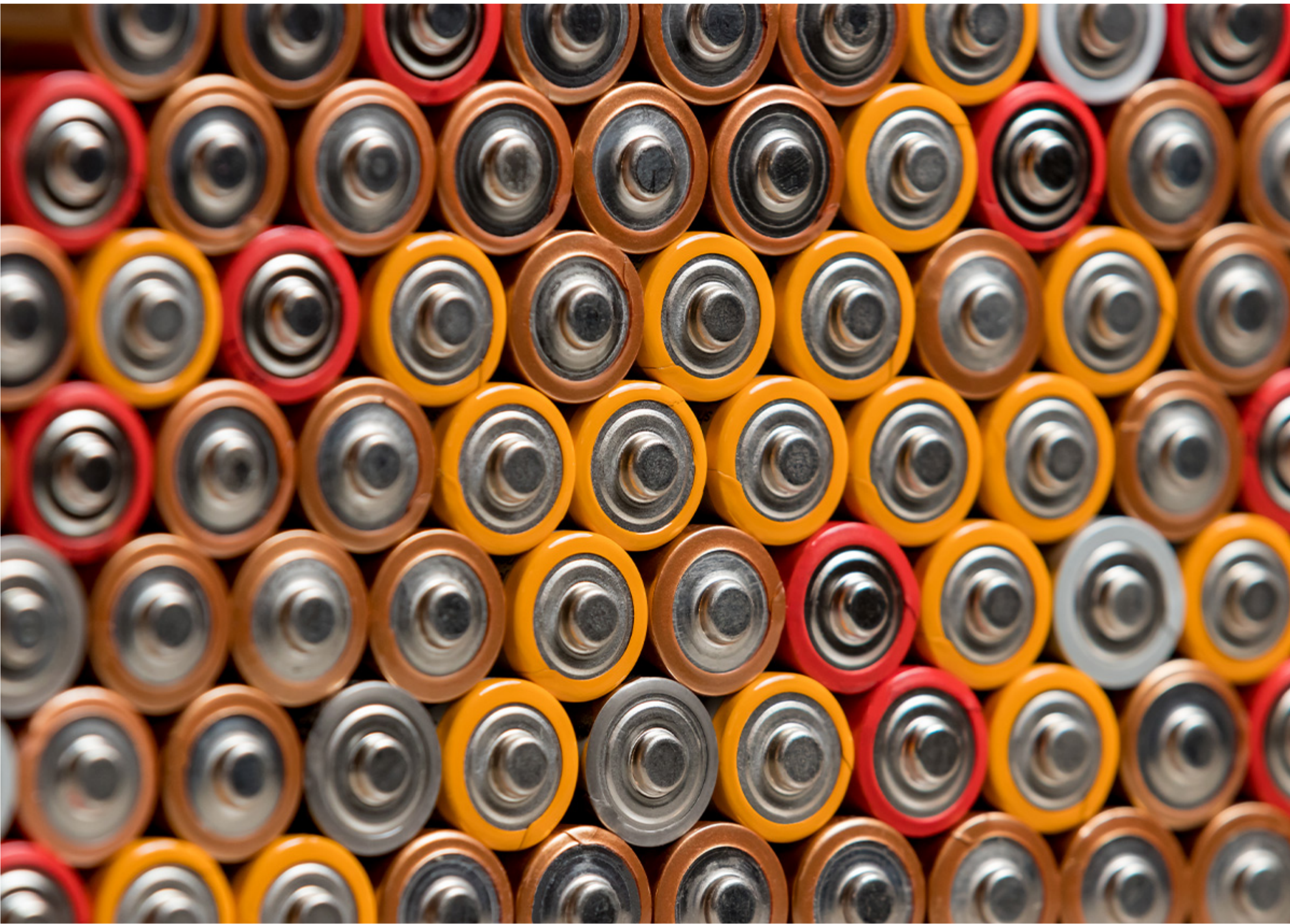
- Appropriate container vessels to reduce fire risks
- Cost effective discharging processes
- Automating the discharge and dismantling process
- Developing local economically feasible technology not limited to metallurgical processes to ensure that we can match the chemical, physical and “form” attributes of recycled products and can tack onto existing material refining processes or mining processes or new processing infrastructure
- Finding more stable solutions to deal with broken, damaged overcharged overheated LIBs
- Develop techno-economic tools to evaluate and optimise recycling technologies

7.8.3 Improved public awareness

Public awareness is one of the key barriers to the future success of Australian battery recycling and reuse industry. Improving public awareness is an essential criteria for all the stakeholders in the battery value chain. Raising public awareness, not only helps increase the recycled waste volume, but also creates a market for recycled material or second-life batteries. From the survey and gap analysis, it was found except for campaigns run by State Governments, some of the recycling companies, such as Cleanaway also run sustainable waste education programmes at local schools educating children about battery recycling. Those programs engage students of all ages (from pre-school to college and TAFE’s) and teach them how to make a sustainable future possible. Planet Ark launched RecyclingNearYou.com.au in November 2006 to help people find out what you can and can't recycle in your household recycling services and locate the nearest drop off network. RecyclingNearYou.com.au receives over 3.7 million pageviews to the site per year. In addition, once implemented and launched the Battery Stewardship Scheme will assist in public education efforts as well. Participating stakeholders suggested:

- Widespread public campaign to promote LCA (life cycle assessment/analysis) and environmental benefits of recycling critical raw materials
- Increasing educational promotion activities
- Local Government Area level action and a National strategy so the messaging is clear
- Provide more collection points in convenient locations, along with standardised messaging across Australia reminding people to not put batteries in household bins
- Pursue compulsory product stewardship program for batteries

Part VIII Summary and opporunities



8.1 Summary, findings and opportunities

8.1.1 Summary and findings

Driven by the growth in transport electrification and energy storage for renewables electricity generation the volume of batteries is growing in Australia and globally. This will lead to an increasing waste stream volume as these devices reach end-of-life in the near-term future. This growing waste stream presents new safety risks as waste is either stockpiled or enters landfill sites. Additionally, without effective recycling and resource recovery, a potential loss of economic value is present. This then presents an opportunity for Australia to increase revenue in the recycling industry and concomitantly grow the industry providing new local job opportunities. Further an effective recycling industry can also assist the broader goals of Energy Security through linking with existing and emerging industries of minerals and resource mining and battery assembly and technology assembly industries to provide technologies for energy storage and low emissions transport.

In the batteries market, the currently dominating lead acid battery will continue to grow, but will eventually be surpassed by lithium-ion batteries. As more electric vehicles and energy storage systems are installed, large sized devices will become the dominate waste form, surpassing the current small consumer electronics battery wastes. Further, as the grid utility scale installations come off-line in the next 10-20 years, a large volume of battery modules will enter the waste stream.

Currently, lithium-ion battery recycling industry struggles to generate reasonable profit margins and economic sustainability due to low volumes of waste available for processing. Thus there is an opportunity through development of collection infrastructure and networks, both expansion of existing e-waste networks and infrastructure and development and implementation of new LIB specific networks and infrastructure to increase waste volumes. In this context, stewardship schemes will assist the collection rates to make waste stream flows viable into the long term. As these large format batteries reach end-of-life the profitability and sustainability will increase. In this context, second-life batteries can be deployed to firstly delay entry of waste into recycling facilities, but to also increase the overall profitability of businesses. Studies have shown that second-life batteries can be price competitive with virgin manufactured batteries and profitable in certain applications. However, the profitability of this emerging business is strongly related to the labour and remanufacturing costs. Technological development to create economically viable second-life batteries and systems and development of new markets are crucial opportunities to develop this emerging industry.

In the battery recycling industry some key challenges have been identified. The first is in the sorting of batteries at facilities. A number of potential solutions have been identified which can resolve this problem:

- Labelling and barcoding or QR coding of battery cells with clear labelling of chemistry type.
- Standardisation of large format battery pack designs.
- State of Health of end-of-life battery packs being made available from manufacturers.
- Automation solutions for sorting with high efficiency and low sorting errors.

The second area is in safety of end-of-life batteries. This is of concern for all areas from collection, transport, second-life remanufacturing and materials recovery. Some potential solutions identified to address this challenge are:

- Discharging solutions for end-of-life batteries.
- Container improvements for end-of-life batteries.
- Clearer policies and guidelines for management of end-of-life batteries.
- Developing closer links and information sharing between policy regulators (e.g. State governments, EPAs etc.) and first responder agencies (e.g. fire, police, paramedics, SES etc.).

Addressing the safety challenge will have a significant affect on the recycling industry through lower HSE risks to people and the environment and also through lowering of high insurance premiums, which are high due to high risk associated with current practices and regulations.

A survey of the policy and regulatory landscape has identified that the battery stewardship scheme can be a driver for growth of Australia's battery recycling industry. However, more work still needs to be done to assist the industry expand to cope with the growing waste streams in the future. Further work needs to be performed to develop recycling standards and policies which are battery specific. In addition, across the entire value chain work needs to be done to improve consumer and public awareness of battery recycling to drastically improve collection and recycling rates in Australia. This consumer and public education campaign could take the shape of a National strategy and be supported by States and Local Government Areas to ensure a unified message to the public is communicated.

One of the challenges identified for the recycling industry is the dearth of unified transportation regulations. Having a set of comprehensive and consolidated transport regulations across all States and Territories in Australia and guidelines for import and export could assist the recycling industry and the battery manufacturing, importing and retail sectors more broadly.

In order to grow the recycling industry in Australia a number of areas were identified which could assist:

- Growing the fledgling second-life and remanufacture industry.
- Development of new regulations and policies for second-life batteries to assist in industry growth.
- Increasing size and quantity of current collection facilities across all of Australia and ensuring more convenient consumer drop off points.
- Government and regulatory support to grow new industry and expand current industry through improvements and development of:
  - Regulations and policies.
  - Standards.
  - Incentives.
  - Public education schemes.
- Development of new markets for recycled products and materials.

- Addressing the high costs of setting up new business ventures through access to funding. It is noted that this can be achieved by having stronger recycling policies in Australia, which then helps to de-risk financial investments for investors.
- Development of new technology for more efficient recovery of materials with high purities needed for manufacturing markets which are at a lower cost than virgin materials.

8.1.2 Opportunities to create greater value in the Australian battery recycling industry

Through in-depth analysis of the current policy landscape, stakeholders identified the following opportunities to strengthen and grow Australia's domestic recycling capability and generate new industries and employment opportunities:

International policy area

1. Improved labelling and barcoding or QR coding requirements for battery cells. An opportunity presents itself for Australia to take a global leadership position in coordinating agreement between international Governments of major manufacturing regions and markets of China, Japan, United States of America and European Union.
2. Guidelines to ensure battery manufacturers and users make available State of Health information for end-of-life batteries. Similar to above an opportunity exists to either influence the current changes to the European Union battery regulations or to setup International Product Stewardship schemes through coordination of major international governments.

National policy and regulation area

3. Exploring a National Product Stewardship for all batteries and assistance for State Governments to establish recycling in each State.
4. Investigating a unified National battery and battery waste transportation policy between Federal, State and Territory Governments and Industry. Industry participants in this report noted that the current transportation policy hinders the recycling industry.
5. Stakeholders identified lack of enforcement of policy as a big business barrier as it gives advantages to unethical processors that are less costly but less effective at achieving good outcomes. There is a clear opportunity here to increase the rate of enforcement to remove these unethical business practices and ensure waste is correctly recovered and recycled in a safe manner.
6. Due to the lack of information and understanding both in Australia and globally, there is a clear opportunity to increase research in this area coordination of state and territory governments, EPAs and emergency response agencies to provide increased safety to the general population and first responders when dealing with battery fires.
7. Investigation of of a National public education campaign with a unified and clear message for battery recycling. There is an opportunity here for a joint State and Territory Government and Industry led scheme to promote consumer awareness of battery (and other e-waste) recycling.
8. A comprehensive review of policies, regulations and guidelines for end-of-life battery waste management. Industry bodies such as ABRI have some guidelines available for public

utilisation, however there is an opportunity to improve/extend these guidelines by Governments and Industry working together to identify key challenges that require new policy and/or guideline changes.

9. Exploration of a Federal level strategy and master plan for the next 25+ years to build long term economic prosperity and value
    d. Investigate regulations regarding keeping waste on-shore
    e. Investigate associated economic and environmental impacts
    f. Identify role of regulatory changes vs. industry led changes needed.
10. Policies and regulations to assist growth of second-life battery remanufacture industry.

Industry development area

1. Increasing consumer collection facilities and improving locations to provide greater convenience to improve collection rates.
2. Improved participation of industry in voluntary stewardship schemes including large scale battery manufacturers, importers and retailers and electric vehicle manufacturers.
3. Growing and expanding current materials recycling and recovery facilities.
4. Setting up new materials recycling and recovery facilities as waste stream grows.
5. Development of techno-economic and market analysis of existing waste industry and emerging waste industries to assist industry in growth and development activities and to help de-risk investment decisions. This opportunity can be achieved through effective partnerships between Industry, Governments and researchers.
6. Development of new markets for recycled and recovered products.
7. Investment in infrastructure and markets for using the materials.

Research area

1. Provide research and solutions for battery fire safety risks during collection, transportation and storage including development of solutions to deal with broken, damaged, overcharged or overheated LIBs.
2. Provide technology advancement, technology support for battery value chain in Australia not only in mining and primary mineral processing, but also downstream in the battery manufacturing, maintenance, and end-of-life treatment.
3. More research into barriers and enablers for Australia to progress up the battery value chain and research and development to support recycling LIBs into high value products – ideally those that maximise the displacement of virgin resources.
4. Research on developing end markets for the recovered battery materials for use in alternative industries. Identification of barriers, technical challenges and opportunities.
5. Develop a decision support tool to ensure sustainability of the battery value chain in Australia.
6. Develop new profitable recycling technologies for low cobalt based batteries.

7. Supported by Industry and Government for commercialisation of developed recycling technology for rapid translation into industry.
8. Facilitate increasing domestic recycling and refurbishment capacity in line with anticipated growth in battery waste volumes.
9. Funding for testing of recycled materials and end-of-life batteries.
10. Hydrometallurgy refinery development to maximise efficiency and reduce energy and water consumption and reduce operating costs.
11. Promote downstream processing. Promote LCA benefits of recycling and reduced value chain emissions from downstream processing in Australia.
12. Development of discharging solutions to make end-of-life batteries safer.
13. Development of automation for improved sorting with low error rates.
14. Development of transport and storage containers for improved safety of batteries.
15. Development of solutions to help standardise large battery packs from EVs and ESSs to assist with remanufacture and recycling at end-of-life.
16. Provide technology development and support to improve materials recycling efficiency and improve costs to help business economic viability.

Appendix A Stakeholder comments

A.1 The greatest hurdle for Australia to have its own battery value chain in the next 10 and 20 years survey results summary sheet

	What do you think the greatest hurdle/barrier is in the next 10 years?	What do you think the greatest hurdle/barrier is in the next 20 years?
Recycling industry	Investment	Investment
	Cost of local manufacture versus other countries	Cost of local manufacture versus other countries
	Funding the capital investment	Funding the capital investment
	Political will. Policy that has both enforcement and good regulation	Political will
	Providing sufficient benefits in Australia for the production of LiB grade Cathode / Anode materials, and in recycling	Ramping up recycling
Manufacturer, importer and retail	Geographical spread and processing infrastructure	Geographical spread and processing infrastructure
	Industry and government support	Funding and strategic partnership with OEM's and battery groups
	Lack of nationalistic interest, market hype	Refilling the holes, federal support & long term federal level strategy, reliance on debt financing, metal price risk management
Not-for profit organisation	Overseas competition, lack of Australian government support	Overseas competition lack of Australian government support
Policy and regulatory	Getting consumers to recycle all their spent batteries and ensuring there are local markets for the recycled materials	
	Domestic infrastructure public awareness, public engagement and industry participation	Public engagement and industry participation
	Regulatory	Regulatory
	Reuse and recycling	Recycling
	Recycling/remanufacturing capacity is limited. Economies of scale and distance to available processing is a challenge. Australia is very reliant on export	Recycling/remanufacturing capacity is limited. National approaches must be established within 10 years to see economies of scale within 20

	What do you think the greatest hurdle/barrier is in the next 10 years?	What do you think the greatest hurdle/barrier is in the next 20 years?
Researcher	Infrastructure	Battery design
	Battery manufacturing/recycling	Battery manufacturing/recycling
	CRC is currently funding projects to add value to the mining industry towards battery manufacturing. Reuse of batteries will be soon a reality for Australia as there are several industry partners working on this area as well as centres and Universities. Recycling is a bit far off as will require safer logistic for collection and storage, followed by the development of a methodology to sustainably recycle	I believe in 20 years Australia will be in a better position to own a battery value chain if research and funding continue. Therefore, economic support could be the greatest hurdle
	Competition from overseas	Cost reduction in Australia
	Recycling technology	Collection and regulation
	Depending on the development of energy storage	Whether the manufacturing, reuse and recycling turns out to be available or economically beneficial, which strongly depends on the value of the elements involved. Government regulation such as product stewardship schemes require an extended producer liability
	Technical constraints, economic barriers, and regulatory gaps	Technical constraints, economic barriers, and regulatory gaps

A.2 The role of Australia in the global battery value chain and its associated risks and opportunities

ROLE OF AUSTRALIA IN THE GLOBAL BATTERY VALUE CHAIN			
Advantage of keeping existing role	**Disadvantage of keeping existing role**	**Advantage of expanding into new industries**	**Disadvantage of expanding into new industries**
		Job creation and reduced supply risk	Will it be economical manufacturing locally versus global competition
Well established first tier industry recovering ethically sourced battery minerals		Significant value adding in developing downstream processing. Reduces the risk in supply chain disruption to global OEM's with an alternative source of battery materials other than China	Requires substantial capital investment and development of markets in what is currently a competitive industry
Provides short term solutions whilst industry develops	Potential for no new industries to develop	Better management of resources, economic growth and job creation, less reliance on trading partners that like strongarm negotiating	If mis managed, it could waste funding that could be used in other areas
		Creating more value in Australia	Australia cannot compete on economies of scale, will likely go only to CAM/Anode stage, but probably not cells/packs. Recycling will be more important in 10-20 years' time
Simplification, high rent upstream	Loss of margin, loss of connectivity to customers, lost ethical sourcing and "green credential" opportunity and reduced value chain carbon emissions, lost opportunity for job creation	Margin creation, jobs, closer connectivity to customers, ethical sourcing and green credentials and reduced value chain carbon footprint	Complexity, lower rent downstream
Securing market share and developing Australian industry		Adapting to the fast changing market and developing a manufacturing industries	
No thinking or strategy required	Lack of metal ratio optimisation, metal basket unchanged	Deliberate strategy to position Australia as primary metal supplier for the battery value chain	Most likely need a consortium of companies and federal level strategy. This will be a more difficult task than keeping the status quo

ROLE OF AUSTRALIA IN THE GLOBAL BATTERY VALUE CHAIN			
Advantage of keeping existing role	**Disadvantage of keeping existing role**	**Advantage of expanding into new industries**	**Disadvantage of expanding into new industries**
All industry has moved to largely automated processes – that means the labour cost advantages of other countries has diminished and Australia's comparative advantage increases due to our more highly educated workforce and good social cohesion and stability. Building from nothing is much more difficult than building upon an existing base		Australia has huge clean energy resources, and massive metals & mineral resources. For all that we allow value adding to be done overseas and do little here. Worse, we extract very low fees for those resources (royalties, resource rent taxes) relative to other countries. For example, in 2017-18, LNG companies in Australia had revenue totalling $29.7 billion, yet paid just $1.07 billion in royalties levied under the petroleum resource rent tax (PRRT). Qatar, a close second behind Australia in production, received a staggering $26 billion in royalties. We do that with every resource – even wool, where we do not even clean it before export, a process that multiplies the value several times. The CSIRO submission in 1999(!) https://www.google.com.au/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiiqs_qiqztAhXfIbcAHdKYClYQFjARegQIIBAC&url=https%3A%2F%2Fwww.aph.gov.au%2FParliamentary_Business%2FCommittees%2FHouse_of_Representatives_Committees%3Furl%3Disr%2Fvaladd2%2Fsubs%2Fsub22.pdf&usg=AOvVaw0_xIi54gg9uTPgckS9cipJ covers many of these. Battery manufacturing and/or recycling is just the latest of many policy failures that keep us locked into digging stuff up or growing it and shipping at low cost & low profit	We remain as we are now - a price taker not a price maker. The current breakdown in our relationship with China highlights the fragility of the supply chains – globally not just for us. Australia is the source of much of the inputs to the China yet could be a competitor in selected high value products
The activities we have already are good, but we can have more sustainable circular economy if we do more of it in Australia	Not evolving with a changing world. Being too heavily reliant on international markets	Expand the opportunities of creating industries and recycling/using our own materials, rather than exporting to raw materials for manufacturing, then re importing once manufactured. Benefits Australian with new jobs, makes our markets more diverse and incentivises new opportunities around the whole supply chain. Makes Australia more self-sufficient, not having to rely on deals with other countries	Manufacturing costs
		Economics, reduced reliance on resources, opportunities for manufacture/ new industries	None that I can see

ROLE OF AUSTRALIA IN THE GLOBAL BATTERY VALUE CHAIN			
Advantage of keeping existing role	**Disadvantage of keeping existing role**	**Advantage of expanding into new industries**	**Disadvantage of expanding into new industries**
Demonstrated competitiveness of existing operations. Existing operations have potential to be leveraged	Missed opportunities for strategic growth, further entrenching current behaviours and supply chain models. The industry may not be well placed to take advantage of future policy changes at state and/or federal	Opportunities for strategic growth and being well placed to take advantage of future policy changes state and/or federal	Investment risk. Recycling infrastructure tends to be a high volume, low margin business. Due to this characteristic, recycling capital asset investments run the risk that feedstock supply disruptions and regulatory change (e.g. regulation which banned single use plastic bags), can lead to assets never achieving profit or meeting a breakeven point. Even where profits are made the payback period for these assets can be long
		Supports a circular economy	Difficult to create new industries in Australia
Reduced short term costs, less resourcing and technology development required	Increased long term waste management costs, increased disposal to landfill and loss of resource. Reliance on international processors to manage/process waste	By creating a viable recycling industry, waste streams entering landfill can be avoided and resources recovered for reuse	Additional costs, rapidly changing battery technologies – high cost of capital of infrastructure to process/recycle batteries that can potentially become redundant as technologies change
Export of waste would be less costly in the short term provided an international market exists. Noting this may not be a viable scenario if waste export is banned	Australia would remain vulnerable to future shocks, commodity prices and international policy regimes if completely reliant on export	Waste export bans and structural change in overseas markets (e.g. China ceasing all solid waste imports) means that expansion of domestic recycling & remanufacturing will be essential	Significant investment will be needed to establish a robust and competitive market
Abundant resources and stringent regulations to ensure ethical mining	Remote to the global battery market	Close to raw materials; Great potential for renewable energy uptake	High labour cost Remote to the global battery market Relatively small domestic market
It is an established role which provides economic support to our economy	We will be missing the opportunity to develop and grow new businesses and to get more valuable materials. This will be also translated into new knowledge and job creation. We strongly depend on other countries economies and policies to buy our mineral. Increase in footprint by exporting our waste	New skilled job opportunities, expand market to export materials, less dependent on materials imports, control the price of materials and reduce price volatility	Large investment in capabilities and therefore capital required
		We have the raw material here and the markets close by in Asia	Domestic market size will always be small

ROLE OF AUSTRALIA IN THE GLOBAL BATTERY VALUE CHAIN			
Advantage of keeping existing role	**Disadvantage of keeping existing role**	**Advantage of expanding into new industries**	**Disadvantage of expanding into new industries**
Use limited government funding support available to secure the key industry where we dominate	Miss the opportunity to expand into the next stage of added value products	Increase robustness of the Australian industry, business and employment opportunities by going beyond the raw commodities	Strong overseas competition. May require legislation changes to encourage local utilisation of the battery materials
		Because there can always be technology change. Suddenly what you think is great	The value change and the logistics behind this

A.3 What can the FBI CRC do to help with the battery value chain in Australia stakeholder responses

	What sort of assistance should the FBI CRC provide to create more value in the Australia battery industry?	What can the FBI CRC do to keep recovered (from recycling) battery materials within the Australian battery value chain?
Recycling industry	More research into barriers for Australia to progress UP the value chain of battery value chain. Let's avoid Australia become the world's 'mine' again! E.g coal, iron ore, bauxite etc…	N/A
	Don't know	I don't think this is important
	No opinion offered	No opinion offered
	Commercialisation of technology	Influence policy makers Provide technology options for making battery grade materials to material miners and processors
	Funding for recycling testing and hydromet refinery development	Develop local capabilities for de-energisation / shredding and refining to LiB CAM/Anodes
Manufacturing, importer and retail	Promote downstream processing. Promote LCA benefits of recycling and reduced value chain emissions from downstream processing in Australia. Existing programs in FBICRC are well geared towards this objective	Develop technology to ensure that we can match the chemical, physical and "form" attributes of recycled products to existing or new processing infrastructure
	Make sure everyone see value in working together	Federal level strategy, master plan for the next 25+ years not just mid-term thinking about value adding once
Policy and regulatory	Push for regulated national Product Stewardship of all batteries Investment in infrastructure and markets for using the materials	Work with policy makers to assist with Circular Economy values – ensuring the first option and best value options for recyclers is to use materials here, rather than exporting. Prioritising processors and manufacturers that will seek for the better recovery option, rather than the cheapest. Product stewardship
	Technological advances & education of the industry and general public	

	What sort of assistance should the FBI CRC provide to create more value in the Australia battery industry?	What can the FBI CRC do to keep recovered (from recycling) battery materials within the Australian battery value chain?
	FBI CRC could focus on understanding barriers and enablers to the domestic battery supply chain. The objective of this work should be to facilitate increase domestic recycling and refurbishment capacity, research and development to support recycling LIBs into high value products – ideally those that maximise the displacement of virgin resources	FBI CRC could support the domestic industry to be cost competitive. An area of focus could be supporting the domestic refurbishment of used LIBS and the cost-effective processing of recovered battery materials into high value products that are comparable with virgin materials
	Research on developing end markets for the recovered battery materials for use in alternative industries	Research on developing end markets for the recovered battery materials for use in alternative industries and liaison on with industries to develop these end markets
	Researching and bringing to market new battery technologies whilst ensuring a circular economy for batteries through reuse and recycling	Provide improved technologies for batteries, battery manufacturing and recycling of materials to provide a circular economy
	R&D into best practice ways to re-use lithium, cobalt and other constituents into high value uses such as new batteries	Accessible processing on-shore with economies of scale and adequate end market demand for the recyclate
Researchers	Provide technology advancement for battery value chain in Australia not only in mining and primary material processing, but also down in the battery manufacturing, maintenance, and end-of-life treatment. Develop a decision support tool to ensure sustainability of battery value chain in Australia	Ensure the equivalent technical performance of recycled battery materials comparing to virgin ones. Develop/proof economic and environmental advantage of recycled materials versus virgin materials
	Assist state governments to establish recycling in each state	
	Create conditions, such as technology and technology support service providers that would help deliver the goals stated above	Perhaps help develop policies and regulations that would enable appropriate legislation
	FBI CRC can contribute in several ways: By measuring the battery waste to manage and track the improvement on battery recycling, reuse and remanufacturing; recording the types and quantities of waste materials generated. By searching the opportunity for another local business which could have a use for the recycled product from the waste battery materials; a search for what materials can be targeted for recycling from the spent batteries. Finding out the options available or feasible to implement recycling. Finding out more about battery waste collection services—how it impacts Australia's ability to recycle. Helping for a overall circular economy for batteries by engaging consumers, industry peak bodies, government, researchers and universities	FBI CRC can conduct the waste audit and/or measure the battery waste to keep track on the variety, quantities, collection rates and efficiency, material flow analysis, etc. to improve the recycling and can do a sustainability review to see if there is room for improvement for all the green efforts. Can work on implementing the recycling program because consumers and businesses cannot conserve and recycle unless a system is in place to collect and separate waste and recycling. Engage with the industry peak bodies, researchers and government to find out appropriate recycling technology by searching the existing and new technologies. Can work on providing the recommended solutions for the policy and guidelines for the battery recycling

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Australian landscape for lithium-ion battery recycling and reuse in 2020

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