Minerals Engineering 128 (2018) 45–55

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Urban mining of lithium-ion batteries in Australia: Current state and future trends

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ARTICLE INFO

Keywords:
Lithium-ion batteries
Recycling
Resource recovery
Trend
Urban mining
Waste

ABSTRACT

With declining ore grades and increasing waste volumes, lithium-ion battery (LIB) wastes are increasingly considered valuable for urban mining for metal recovery and re-use. In Australia, LIB is not classified as hazardous, despite having significant human and environmental health risks if handled and disposed of improperly. Unlike in Europe and Asia, regulations or policies to enforce or encourage product stewardship are lacking, with small recycling schemes targeting only consumer behaviour, and voluntary actions of manufacturers and distributors. Although manual sorting and dismantling of LIB waste occur onshore, the valuable components are shipped overseas for processing due to limited onshore capacity to recover the inherent metal values. In this paper, LIB recycling in Australia is reviewed, considering the projections of LIB waste generation, identification of future trends, opportunities and potential for innovation for LIB recycling in Australia. Key gaps surrounding materials tracking, waste generation and fate and technology design need to be addressed to support the development of the industry and to support the use of primary minerals and materials in Australia.

1. Introduction

Lithium-ion batteries (LIB) contribute to growing waste streams as a direct result of increasing use of and demand for handheld, portable and rechargeable equipment. The importance of recycling of LIB is growing as the global production of LIB is predicted to increase 520% between 2016 and 2020 (Desjardins, 2017). It was also reported that in Australia alone, the generation of end-of-life LIB was growing at a rate of 19–22% per annum (Randell, 2016), primarily driven by the increasing uptake of energy storage systems and electric vehicles (Asghar, 2016). At the same time, there are compounding pressures on the availability of global primary mineral reserves (Hatayama et al., 2015; Mudd, 2009), and accessibility and societal issues for some of the more critical resources such as cobalt (Nansai et al., 2014; Nazarewicz, 2016).

LIB present significant, unique and complex waste management issues (Pagnanelli et al., 2016; Zeng and Li, 2014; Xu et al., 2008). As technology develops more rapidly, the lifespan of current technology is shortened, and the consumption of portable and handheld devices simultaneously increases. The metallic fractions of LIB waste, which can include metals such as cobalt, lithium and base metals, making it extremely valuable and support the economic feasibility of recycling LIB waste (Boxall et al., 2018; Zeng et al., 2014). However, the variability in structure and chemical composition of LIB from individual manufacturers as well as the collection, sorting and handling of these wastes presents some challenges for processing. There are several types of rechargeable LIB in circulation that use various compositions and cathode chemistries for operation (Table 1). These include, but are not limited to, lithium cobalt oxide (LCO; $LiCoO_2$), lithium nickel manganese cobalt oxide (NMC; $LiNiMnCoO_2$) and lithium iron phosphate (LFP; $LiFePO_4$) batteries. As such, the resulting waste streams can vary in composition, and this can impact processing and recovery of value from these wastes. An example of the variable composition of LCO, NMC and LFP batteries are shown in Fig. 1 (Golubkov et al., 2014).

Much of the technical literature has focussed on the development of technology suitable for the recovery of value from e-waste. A significant proportion of the research conducted to date has investigated the modification of well-established mineral processing techniques such as hydrometallurgy and pyrometallurgy (Pagnanelli et al., 2016; Zeng and Li, 2014; Xu et al., 2008). Also, the application of various combinations

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https://doi.org/10.1016/j.mineng.2018.08.030
Received 25 June 2018; Received in revised form 9 August 2018; Accepted 24 August 2018
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Table 1
Lithium battery types (modified from Gratz et al., 2014; AAS, 2017; Lewis, 2016).

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

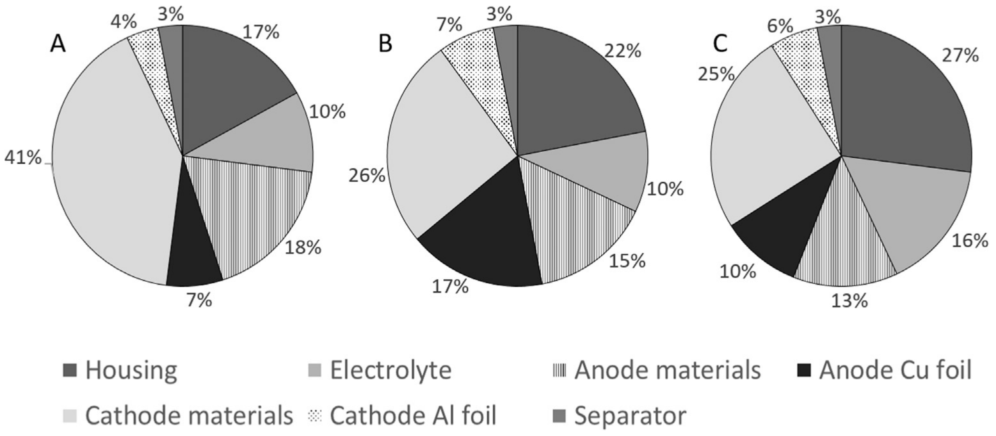

Fig. 1. Variability in the structure and composition of LIB with varying chemistries (modified from Golubkov et al., 2014). LIB types shown here are A: lithium nickel manganese cobalt oxide cathode; B: lithium cobalt oxide cathode; and, C: lithium iron phosphate. The different structure and composition of these batteries impact processing due to the heterogeneity of feedstocks.

of reagents and the impact of pre-processing on downstream metal recovery has also been studied (Boxall et al., 2018; Hong and Valix, 2014). However, only a small number of commercial operations exist globally for the recovery of metals from LIB waste. These are mostly located in Asia and Europe, where the drive to recover value from wastes and closing-the-loop for the manufacture of electronic equipment and devices is well regulated and driven by policy (Heelan et al., 2016).

Australia is at a crossroads when it comes to the management of these valuable waste streams. Currently, in Australia, LIB wastes are not classified as hazardous wastes, despite having significant human and environmental health and safety risks if handled and disposed of incorrectly (Randell et al., 2015). Unlike our European and Asian counterparts, there are no regulations or policies to enforce or even encourage product stewardship, with small recycling schemes targeting the behaviour of the consumer, and voluntary actions of manufacturers and distributors, mostly for mobile phones. Likewise, there are no dedicated recycling processes onshore in Australia that can recover the inherent value from these wastes (Lewis, 2016; Randell, 2016). Collection rates are low, with less than 2% of LIB recovered and the rest sent to landfill for disposal, with the potential to cause irrecoverable damage to the environment (Lewis 2016; Randell, 2016; Randell et al., 2015). For LIB waste that is collected, the labour to dismantle and sort the waste occurs onshore in Australia, and then the value recovered is sent offshore for further processing (Lewis, 2016). As a result, the value contained within these waste stream is lost to international economies instead of being retained in Australia. Questions regarding the off-shore processing of hazardous wastes, issues with transport safety, along with increasing generation of LIB waste and changing policy environment means that Australia has the perfect storm required for innovation and technology development specifically related to the recovery of value from LIB waste.

This review paper considers the current practices for LIB recycling in Australia with regards to the ability to locally recover and retain or re-use value from LIB. The projections of LIB waste generation are discussed, and the future directions and significant bottlenecks for LIB recycling in Australia are identified to evaluate how these may be addressed to develop a sustainable industry for LIB recycling in Australia. The recovery of value from these wastes presents an opportunity to harness Australia's well-developed mineral processing technical expertise, with the goal of supplementing the use of primary minerals and materials, such as plastics and graphite, in Australia.

2. Current trends and fate of spent LIB in Australia

The sales of rechargeable LIB in Australia have grown sharply since 2003/04, and in 2015, they accounted for 24% of all batteries purchased in Australia (O'Farrell et al., 2014). In 2016, it was reported that 3340 T of LIB reached their end of life (Randell, 2016). This report also indicated that only 2% of the LIB waste was collected for recycling in Australia. LIB recycling in Australia, however, encompasses essentially the collection and breakdown of LIB into smaller waste streams that can be easily exported offshore for further processing (Lewis, 2016; Randell, 2016). The remaining LIB waste generated in Australia was still sent to landfill or stockpiled (both formally and informally) (Lewis, 2016; Randell, 2016). There are significant environmental and human health implications surrounding the incorrect handling and disposal of LIB, and this has been well discussed in the literature (for review see: Zeng et al., 2014).

The development of technology for resource recovery from LIB wastes in other countries in Europe and Asia, for example, has primarily been driven by policy and regulations that ban landfill disposal (of all wastes in some countries, like Germany). Also, these regions have set resource recovery targets from specific waste streams and provide incentive or penalty to manufacturers and distributors when they are not achieved (Directive 2006/66/EC of the European Parliament and of the

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