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Economies of scale for future lithium-ion battery recycling infrastructure

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ABSTRACT

While lithium-ion battery (LIB) technology has improved substantially to achieve better performance in a wide variety of applications, this technological progress has led to a diverse mix of batteries in use that ultimately require waste management. Development of a robust end-of-life battery infrastructure requires a better understanding of how to maximize the economic opportunity of battery recycling while mitigating the uncertainties associated with a highly variable waste stream. This paper develops and applies an optimization model to analyze the profitability of recycling facilities given current estimates of LIB technologies, commodity market prices of materials expected to be recovered, and material composition for three common battery types (differentiated on the basis of cathode chemistry). Sensitivity analysis shows that the profitability is highly dependent on the expected mix of cathode chemistries in the waste stream and the resultant variability in material mass and value. The potential values of waste streams comprised of different cathode chemistry types show a variability ranging from $860 per ton[1] for $LiMn_2O_4$ cathode batteries to $8900 per ton for $LiCoO_2$ cathode batteries. In addition, these initial results and a policy case study can also help to promote end-of-life management and relative policymaking for spent LIBs.

1. Introduction

Lithium-ion batteries (LIBs), a type of rechargeable battery, have been widely used in consumer electronics (e.g. cellular phones, laptop computers, digital cameras, etc.) for decades. More recently, LIBs have also been used to power electric vehicles (EVs), gradually replacing nickel metal hydride batteries. The market penetration of EVs is expected to increase as gasoline prices rise and pressure increases to reduce carbon emissions from fossil fuel use (Notter et al., 2010). According to a study done by Roland Berger Strategy Consultants, the global automotive LIB market is expected to reach more than 9 billion dollars by 2015 (Russo, 2012). LIBs in most consumer products have a lifespan of less than 3 years and those in hybrid and all-electric vehicles are projected to have a lifespan of roughly 10 years (Lain, 2001; Marano et al., 2009). Given these low lifespans as well as increasing production, a rapidly growing battery waste stream is likely. In the US, CA and N Y state legislators have attempted to proactively address this waste challenge by issuing state disposal bans on rechargeable batteries (Rechargeable Battery Recycling Act, 2006; New York Environmental Conservation Law, 2011). However, infrastructure required to recycle batteries diverted from the landfill is still lagging. While some companies have developed recycling processes (e.g. Toxco and Umicore) and some companies have sprung up to take on collection (e.g. Call2Recycle), a fully operational, broadly reaching recycling infrastructure for end-of-life (EOL) LIBs is not well developed and the costs of such infrastructure have not been examined in depth.

From an environmental perspective, the ability to recover materials (e.g., cobalt and nickel) from waste LIBs and return them to new battery production has the potential to reduce the battery's life cycle impact by about 51%, when comparing natural resources consumption from using only primary materials (Dewulf et al., 2010). In addition, increasing concerns about leaching potential of some hazardous materials contained in LIBs during landfill disposal also drive relevant research studies (Lowry and Casman, 2009).

Economically, recycling has also traditionally offered an opportunity to recover valuable materials used in battery production, namely cobalt, which is widely used in LIBs due to its high energy density. However, cobalt is a costly metal, and manufacturers are moving toward low-cost cathode materials to reduce the cost of battery manufacturing. Cathode materials such as lithium iron phosphate and lithium manganese-spinel are projected to be the next generation of LIB technology (Ritchie and Howard, 2006). The transition from expensive cathode materials to less expensive options reduces the economic incentives to recycle those batteries at their end of life. However, the technology trajectory of LIB cathode chemistries dominating future production volumes is unclear

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[1] The word "ton" in this paper indicates metric ton (1000 kg).

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Table 1
Indices' information.

Variables	Indices	Notes	Variables	Indices	Notes
	1	$LiCoO_2$		3	Lithium
i	2	$LiFePO_4$		4	Manganese
	3	$LiMn_2O_4$	*j*	5	Iron/Steel
j	1	Cobalt		6	Aluminum
	2	Nickel		7	Copper

and not necessarily predictable; single recycling facilities will likely see a co-mingled stream. All these uncertainties bring difficulties to LIB recycling.

This highly variable battery waste stream is likely to find parallels in the challenges currently observed for managing the larger electronic waste (e-waste) stream. Existing recycling programs for e-waste have been discussed extensively in the literature. Kang et al. and many others have pointed out the increasing volume of e-wastes and outlined the variety of existing recycling programs in the US and their related collection methods (Kang and Schoenung, 2005). Their work provided a review of U.S. infrastructure for e-waste recycling at a broad level and pointed out domestic infrastructure is insufficient to manage this growing waste stream. However, their discussion did not go into detail for individual recycling facilities or raise issues specific to EOL LIBs. Kahhat et al. (2008) reviewed e-waste management systems outside the U.S., including the European Union, Japan, South Korea, and Taiwan, to evaluate the feasibility in the U.S.; and then based on those existing international e-waste management programs and the specific culture in the U.S., proposed an e-waste collection system named "e-Market for Returned Deposit". However, for LIBs specifically, this proposal would require adjustment because (1) direct reuse may not be an option due to their low-performance after regular life time (Gaines, 2011), and (2) unlike other types of e-waste, LIBs are much smaller and they are usually being sold along with electronic products, not individually. Ponce-Cueto et al. (2011) have studied the reverse logistics model, including collection and recycling systems, for recovering mobile phones in Spain. The requirement of high volume of mobile phones to ensure recycling plants being profitable has been discussed together with the reality of low collection rate of EOL mobile phones.

Considering the challenges and knowledge gaps identified in the broader e-waste literature, it is clear that a more proactive approach must be taken to develop a robust LIB recycling infrastructure. To date, an analysis of profitability and trade-offs of recycling have not been applied to EOL LIBs. From a recycling firm's perspective, it will be essential to forecast economic feasibility of LIB recycling, given uncertainty and variability in cost, volume, and profit. The goal of this paper is to examine the economic feasibility of recycling spent LIBs under possible scenarios of waste stream volume and composition. An optimization model is used to assess these scenarios, which include compositional variability (i.e., by cathode chemistry type, or manufacturer) for different LIB types, and chemistry distribution of the overall battery waste stream.

2. Method

2.1. Optimization model

This study develops an optimization model, Eqs. (1)–(5), to identify the minimum amount of spent LIBs (T) for a recycling facility to be profitable based on the costs and revenue (R), assuming all metallic materials contained in LIBs can be recovered at an average recycling efficiency respectively (RE_j). The indices in Eqs. (3)–(5) are shown in Table 1. The costs includes the variable cost (VC) and the annual fixed cost (FC). LIBs come in many different sizes, form factors, pack configurations, and cathode chemistries; therefore the LIB scrap stream will likely be co-mingled. In this study, three types of cathode materials have been considered: $LiCoO_2$, the most common, and $LiFePO_4$, and $LiMn_2O_4$, emerging cathode chemistries likely to be in EVs (Hernandez, 2011; Lucas, 2012). To illustrate how the proportion of each cathode chemistry type (α_i) can affect our result, the break-even amount (T) has been analyzed for several possible chemistry-distributional scenarios of a co-mingled LIB scrap stream. The unit revenue (R) was determined using commodity values of recoverable materials from one ton of co-mingled spent LIBs. The potential value of each type of metal being recovered from one specific LIB cathode chemistry type was calculated based on the material composition of that kind of LIB ($Ava_{i,j}$), recycling efficiency (RE_j) for each type of metal, and primary commodity market price for each type of metal (P_j). The minimum amount of LIBs for a recycling facility being profitable was identified by calculating the break-even point, meaning annual revenue is equal to the sum of fixed and variable costs.

$$Min \cdot T \tag{1}$$

$$St. T \times R - (FC + VC \times T) \geq 0 \tag{2}$$

$$R = \sum_{i=1}^{3} (\alpha_i \times \sum_{j=1}^{7} (P_j \times Ava_{i,j} \times RE_j)) \tag{3}$$

$$\sum_{i=1}^{3} \alpha_i = 1 \tag{4}$$

$$0 \leq \alpha_1, \alpha_2, \alpha_3 \leq 1 \tag{5}$$

2.2. Base case: current battery waste stream

2.2.1. Composition

In the base case, only $LiCoO_2$ cathode batteries are considered since they currently dominate the battery market for consumer electronic products. Further, the base case only considered 18650 cylindrical cells,[2] as these are the most commonly used in electronics like laptop computers, and they can provide a fair comparison between different manufacturers and, in later sections, the different cathode chemistries. Sensitivity analysis conducted in a companion paper (Richa et al., 2013) demonstrated that the total volume and basic material breakdown of an EOL LIB waste stream will not change significantly if prismatic form factor is considered, particularly for LIBs in EVs.

It is expected that the material composition in LIBs would vary significantly between different cathode chemistry types; however, even considering the same cathode chemistry, batteries made by different manufacturers are likely to show variation in their bills of materials (BOMs). The BOM for $LiCoO_2$ cathode batteries from seven manufacturers, including Panasonic, Lishen, Sony, Moli, AT&T, Sanyo, and Matsushita, has been provided in Supplementary Information Table S1 as adapted from (Wang et al., 2013). The average material composition for all of the previously sampled $LiCoO_2$ cathode batteries was calculated and used in the base case (see Table 2). Variability in composition for $LiCoO_2$ cathode LIBs from different manufacturers and its associated impacts on the break-even point has been analyzed in Section 3.3.1 by using the maximum and minimum value.

[2] The 18,650 form indicates the battery is cylindrical, has a diameter of 18 mm, and length of 65 mm.