

The Optimal Reverse Logistics Network for Consumer Batteries in North America

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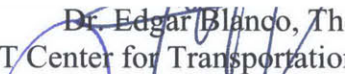
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MIT System Design and Management Thesis:

The Optimal Reverse Logistics Network for Consumer Batteries in North America

Researching, Defining, and Evaluating Available Alternatives

By

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Submitted to the System Design and Management program in partial fulfillment of the requirements for the degree of Master of Science in Engineering and Management

Abstract

The recycling of household consumer batteries is gaining legislative support throughout North America. The intent of this thesis document is to provide a broad overview of the current North American reverse logistics network for consumer batteries. Topics discussed include the viability of recycling for particular battery chemistries, collection methods, recycling methods, the current legislative environment, and the incentives to participate in the reverse logistics network for the various stakeholders identified. This document culminates in the explicit high-level definition of the available reverse logistics networks and the execution of a global warming potential analysis for each network.

It is shown that, of the two available reverse logistics networks, in terms of kg CO₂ equivalents generated per metric ton of batteries processed one network is approximately double the environmental impact of the other. However, despite the magnitude of this difference, in an overall context this difference may not outweigh other factors for consideration. These other factors include cost, materials recovered, and overall environmental impact which would consider ecosystem quality and human health. This research was conducted using available public information as well as interviews with key individuals who are directly participating in the reverse supply chains.

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1 Preface

1.1 Introduction

As consumers grow more environmentally conscious, the landscape for consumer battery recycling is rapidly evolving in North America. This is due to many forces including regulatory pressures, technological advancements, and demonstrated viability through extended producer responsibility. For the scope of this paper, consumer batteries are defined as those batteries typically used in household devices. Typically they are found in an AA, AAA, C or D form factor, but may also include cell phone batteries and laptop batteries as well as others. The primary chemistries of these batteries are: Alkaline, Nickel Metal Hydride, Nickel Cadmium, and Lithium Ion. As our society continues to move toward the recycling of consumer batteries, we must ensure we understand and optimize the reverse supply chain to avoid any adverse environmental consequences. Through a carbon footprint analysis of the existing reverse logistics networks as well as relevant scenario analyses, this paper will attempt to provide the reader with a greater understanding of the current and potential environmental ramifications of consumer battery recycling in North America.

Though neither the U.S. nor Canada has taken action at a national level to regulate consumer battery recycling, much legislation has been put forth (and in some cases has passed) at the state and province levels. Significant legislation has been put forth in the following states and provinces; California, Washington, Minnesota, New York, Rhode Island, Ontario, Manitoba, Quebec and British Columbia. These regional regulations have caused consumer battery recycling to build momentum among consumers, retailers, recyclers, and producers who see more widespread legislation as inevitable. This Thesis will present a comprehensive overview of the legislation in place and currently being proposed.

As demonstrated in the life cycle analysis published by Olivetti, Gregory, and Kirchain, technological advances have enabled us to viably recycle Alkaline batteries. This is of great importance, since Alkaline batteries make up more than 85% of the consumer waste stream¹. Given the large amount of Alkaline batteries in the consumer battery waste stream, without the technology to viably recycle Alkaline batteries, a holistic recycling process is not possible. This paper will compare and contrast the energy requirements of two different alkaline recycling

¹ (Sova, 2013)

processes and will demonstrate to the reader the importance of energy efficient, environmentally conscious recycling practices.

Extended producer responsibility is an idea that has been put into place successfully in Europe as well as Japan, and may have a role in the development of the North American consumer battery recycling system. In both Europe and Japan, extended producer responsibility is applied successfully to batteries, various types of e-waste, and appliances, among many other areas. The North American primary battery producers are keenly aware of the potential for legislated extended producer responsibility and have attempted to get ahead of any legislation through the formation of the Corporation for Battery Recycling (CBR). The producers and/or sellers of secondary batteries in North America have long faced extended producer responsibility pressure, primarily due to the toxicity of their battery chemistries, of which Nickel-Cadmium is the main offender. These firms joined together to form the Rechargeable Battery Recycling Coalition (RBRC) in 1994 in an attempt to successfully deal with Nickel Cadmium recycling legislation. The RBRC has now created the Call2Recycle organization to more broadly influence the developing North American consumer battery reverse logistics network.

While the factors identified and discussed above are helping to drive North America toward a holistic system for consumer battery recycling, the true success of this system will be dependent upon the design of the reverse supply chain. This means we must have efficient collection systems, aggregation points, logistic flows, and recycling processes to ensure significant collection of batteries in the consumer waste stream and minimal carbon footprint for the reverse supply chain process. This paper will examine existing battery collection and recycling systems and their corresponding material flows in an attempt to showcase the overall potential for battery collections as well as the ideal material flows from a carbon footprint perspective.

1.2 Research Motivation

A point of emphasis in the System Design and Management (SDM) program at MIT is the unique education we are given that enables us to understand, communicate, design and influence large scale systems. Courses such as “Systems Architecture”, “Systems Optimization”, and “Systems Safety” help to develop our skills in tackling large scale issues with broad societal

impact. While this education can certainly be seen as a gift given by our faculty to us the students, it is my belief that it is also a responsibility accepted by the SDM student body. The large scale system that will be needed to tackle the issue of consumer battery recycling in North America is both a relevant and timely topic, and is an area in which my professional interests collide with the systems thinking expertise I have gained while studying in the SDM program.

Prior to studying at MIT and concurrent with my education here, I have been working in the battery industry in a variety of manufacturing and corporate roles. My current role is as the Vice President of Quality Assurance for BatteriesPlus, a 550 store retail chain that is the largest battery focused retailer in the United States. Having been involved in the production and distribution of batteries nearly my entire career, I am often asked by friends and family what they should do with their spent batteries – could they just throw them out, or did they need to be recycled? For many years, I did not know the correct answer. As this paper will show, I now have a good understanding of the many ways in which consumers can participate in the battery recycling reverse logistics system.

Within the past 3 years I have become professionally aware of the changing regulatory environment surrounding battery disposal and recycling. Having developed a systems thinking mindset from my time in SDM, and having a better understanding of carbon footprints and reverse logistics from Professor Edgar Blanco's "Green Supply Chain Management" course – I identified a potential issue with the regulatory push toward battery recycling. To successfully recycle consumer batteries means doing so with as little carbon footprint as possible. Regulating the recycling of these batteries does not ensure that it is done in an efficient and environmentally conscious way. The goal of my research then has become to understand the current landscape of consumer battery recycling in North America and propose ways that it can be implemented that are efficient and environmentally responsible from a reverse supply chain perspective.

I am hopeful that I may utilize what I have learned during the process of researching and preparing this thesis may enable me to better exercise my influence the battery industry. Prior to this research I would have only thought of the available reverse logistics networks as being equal, and that our organization should utilize the network with the lowest total participation cost. I now understand that these networks may vary greatly in their environmental consequence and further also understand the drivers that create the most significant environmental impact. As

an executive at the largest battery specialty retailer in North America, I hope that I can enable our firm to become better consumers of battery recycling systems.

2 Foundational Concepts

2.1 Reverse Logistics

Reverse logistics is a term often thought of as the network of activities and material flows for a product after it's consumption through to it's eventual disposal, re-use, or recycle. This term was formally defined by Rogers and Tibben-Lembke in their 1998 paper "Going Backwards: Reverse Logistics Trends and Practices" as follows:

"The process of planning, implementing, and controlling the efficient, cost effective, flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal".

Figure 1 illustrates the role of reverse logistics in the supply chain², wherein the traditional supply chain activities are represented in blue and the reverse logistics activities are shown in orange. The reverse logistics process is shown to begin at the point of use and end at either disposal or re-use. When evaluating the effectiveness of reverse logistics systems, an important distinction to make is whether or not the system contributes to a "closed-loop supply chain". A closed-loop supply chain is one in which the material recovered through the reverse logistics flow is re-introduced to the original user of the material (a.k.a. the Producer). In many cases, though raw materials are recovered through reverse supply chain activities, they are not of sufficient quality to be re-introduced to the production process that they originally supported – thus, they do not support a closed-loop supply chain.

It is important to note that reverse logistics does not necessary imply recycling, this can be further noted by the absence of an explicit recycling process in the aforementioned diagram. Items in a reverse logistics network may reach the point of re-use as original and whole parts, or as their constituent raw materials. Should recycling occur in a reverse logistics system, it would be represented by the Re-Processing (Recovery) process. However Re-processing (Recovery) may also refer to a cleaning/sterilization process (as with some glass beverage containers), an evaluation process (as with some electronic waste), or any other intervention needed to ensure the reusability of items in the reverse logistics network.

² (Blanco & Ponce, 2012)

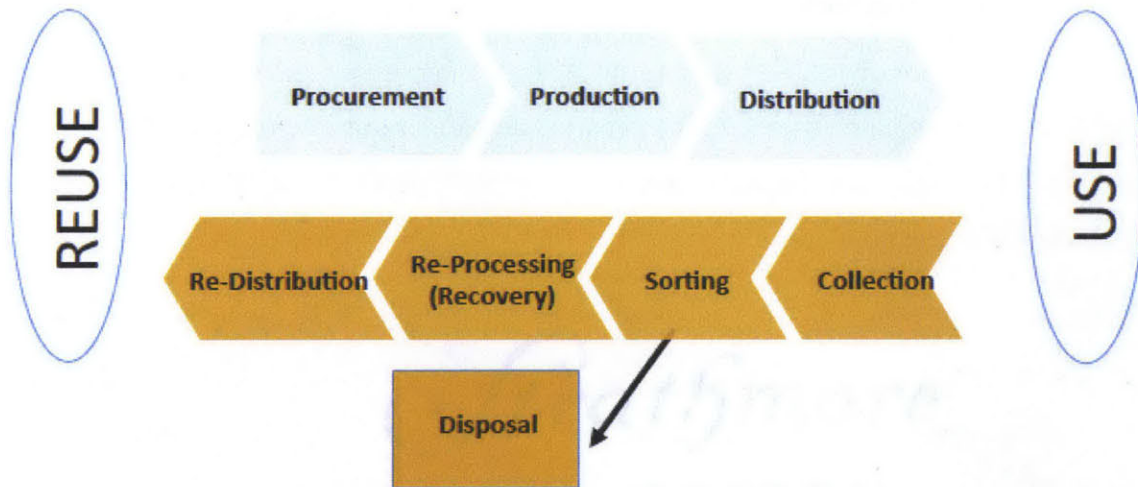


Figure 1: Activity Based Diagram, Forward and Reverse Logistics
 (Blanco & Ponce, ESD.S43 Green Supply Chain Management, Lecture #1, 2012)

2.2 Extended Producer Responsibility (EPR) and Product Stewardship

Extended Producer Responsibility (EPR) is a central concept to the viability of reverse logistics systems and specifically consumer battery recycling. First introduced in 1988 by Professor Thomas Lindhqvist of Lund University in Sweden, the basic idea of EPR is to mandate that the producer be responsible for the product through end of life and disposal, re-use, or recycling³. For this reason, EPR laws are sometimes also referred to as “take-back” legislation. This shifting of responsibility alleviates a burden that is currently often borne by consumers and/or municipalities. In the absence of EPR, the true cost born by the consumer/municipality is often more than just financial but often environmental as well; manifesting as increased amounts of waste, pollution and in some cases hazardous wastes⁴. In many cases EPR applies not only to the product, but to the packaging as well. An additional benefit of EPR is that producers will begin to design the product with end of life in mind, which is expected to lead to design improvements that foster ease of recycling and re-purposing.

EPR is actually thought of as a subset of a broader concept called “Product Stewardship” which is defined as:

³ (Motavalli, 2011)

⁴ (Ogushi & Kandlikar, 2007)

The act of minimizing health, safety, environmental and social impacts, and maximizing economic benefits of a product and its packaging throughout all lifecycle stages⁵.

Product stewardship does not necessarily imply producer responsibility only, but rather recognizes the diverse stakeholders involved in the product life cycle and seeks for each of these stakeholders to play a role in minimizing lifecycle impact of the product. The next two sections focus on the legislation that has passed in both Japan and Europe. It will be shown that this legislation runs the spectrum of pure producer responsibility all the way through to a more balanced stakeholder approach.

⁵ (Product Stewardship Institute, 2012)

3 Influences

3.1 Japan

The first significant Japanese EPR legislation targeted specifically at manufactured product (vs. a specific focus on packaging) was ratified in 2001. Three laws established a framework for product stewardship programs that would grow to cover a variety of industry sectors. The first of these laws is known as the “Fundamental Law for Establishing a Sound Material-Cycle Society”; it helps to establish the roles and responsibilities of all significant stakeholders within the product lifecycle. The second law, known as the “Waste Management Law”, mandates the measurement of critical waste stream metrics that specifically relate to the concept of “reduce, reuse, recycle”. This law applies to 10 industries and 69 unique product items. The final law is known as the “Law for Promotion of Effective Utilization of Resources”, which applies to the operations of waste management and contains guidelines for specific categories of waste. In addition to these framework laws, specific laws have been enacted in certain consumer segments. These are as follows: Home Appliance Recycling Law (2001), Construction Material Recycling Law (2002), and the End of Life Vehicle Recycling Law (2004).

Key features of the Japanese legislation include mandatory take-back requirements, recovery rate targets, and shared stakeholder responsibility. The mandatory take back requirements and recovery rate targets have helped foster R&D spending among manufacturers to determine improved methods of product design and improved methods of product disassembly. Design for disassembly, marking for identification of materials, and reduction of hazardous substances have been pursued by Japanese manufacturers with some success⁶. The innovations developed through these disciplines may help to lead to long term competitive advantage for Japanese industries. .

3.2 Europe

Europe most often leads the way in terms of environmental protections and supporting legislation. In the case of waste recycling in general, and battery recycling in particular, the primary method of European Union legislation has been through Extended Producer

⁶ (Ogushi & Kandlikar, 2007)

Responsibility schemes. The first European EPR legislation was introduced in Germany in 1991 and sought to pass end of life responsibility for product packaging to product manufacturers⁷. This same idea of EPR can be seen in the European Union’s most extensive reverse logistics directive, the Waste Electrical and Electronic Equipment (WEEE) directive. Introduced in 2002, this directive applied to 10 distinct product categories within the electrical and electronic equipment space. This directive mandated EPR along with specified collection rates to ensure effectiveness of the collection programs. Figure 2 shows the well known “wheely-bin” symbol, which was developed as a result of the WEEE directive.

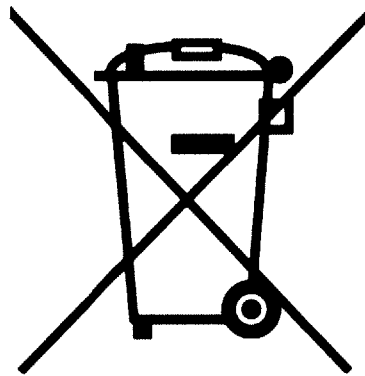


Figure 2: “Wheely-Bin” symbol

This landmark legislation features prescribed collections rates and assigns the costs for the collection and recycling process.

Despite addressing 10 categories of electronic and electrical equipment waste as part of the WEEE directive, the EU had still not broadly addressed the reverse supply chain for consumer battery waste until issuing the Battery directive in 2006. This directive mandated that consumer batteries would no longer follow the typical consumer waste stream, but would rather be collected and processed separately from general waste. Responsibility for collection and recycling was shifted to both producers and retailers, and collection targets along with future increases in these targets were established.

3.3 Reverse Logistics Systems (working models)

Though the term reverse logistics was coined in 1998, examples of reverse logistics systems have existed before that time. To better illustrate the reverse logistics process to the

⁷ (Motavalli, 2011)

reader, this section of the paper will profile a working reverse logistics system. One of the more widely utilized reverse logistics systems which should be relatable to the reader is that for cardboard. While there may be many variants of the reverse logistics process for cardboard, for the sake of clarity the example presented will focus on the reverse logistics of a single municipality, Dane County, Wisconsin. After profiling this system, we will compare and contrast it to a typical EPR mandated reverse logistics network.

Cardboard may be consumed in a residential or a business setting, in either of these settings, there will be a collection point (a bin or dumpster) for subsequent municipal collection. In the case of the home there is typically only one centralized collection point, while a business may have several local collection points that are aggregated at some regular interval for subsequent municipal collection. It is important to note that these individual collection points are not solely for cardboard, but rather for mixed recyclables (cardboard, paper, plastic, metals). To minimize fuel costs as well as resource requirements, municipal collection is paired with existing waste collection services. Each individual collection point is aggregated and transported via truck to a centralized sorting facility. At this facility, cardboard is separated from the other recyclables through a variety of sequential processes including, manual sort, magnetic separation, and automated mechanical separation. The result is baled cardboard that is ready for transport to the recycling center.

Cardboard is transported to the recycling center in full truckload quantities. Cardboard is able to follow a closed loop supply chain, meaning that it is re-introduced to the forward supply chain in the same industry that originally processed it from virgin material, in this case wood fiber. Thus, the “recycling center” for cardboard is actually a paper mill, specifically a paper mill that produces linerboard paper. This is the type of paper that is used for brown paper bags and in the construction of corrugated cardboard products. Upon arrival to the paper mill, the cardboard is introduced to a pulping process where it is broken down into individual fibers. These fibers are then subjected to a de-inking process as well as specific gravity based sorting process to ensure that only wood fiber is re-introduced to the forward supply chain. Figure 3 details the reverse logistics flow for cardboard material.

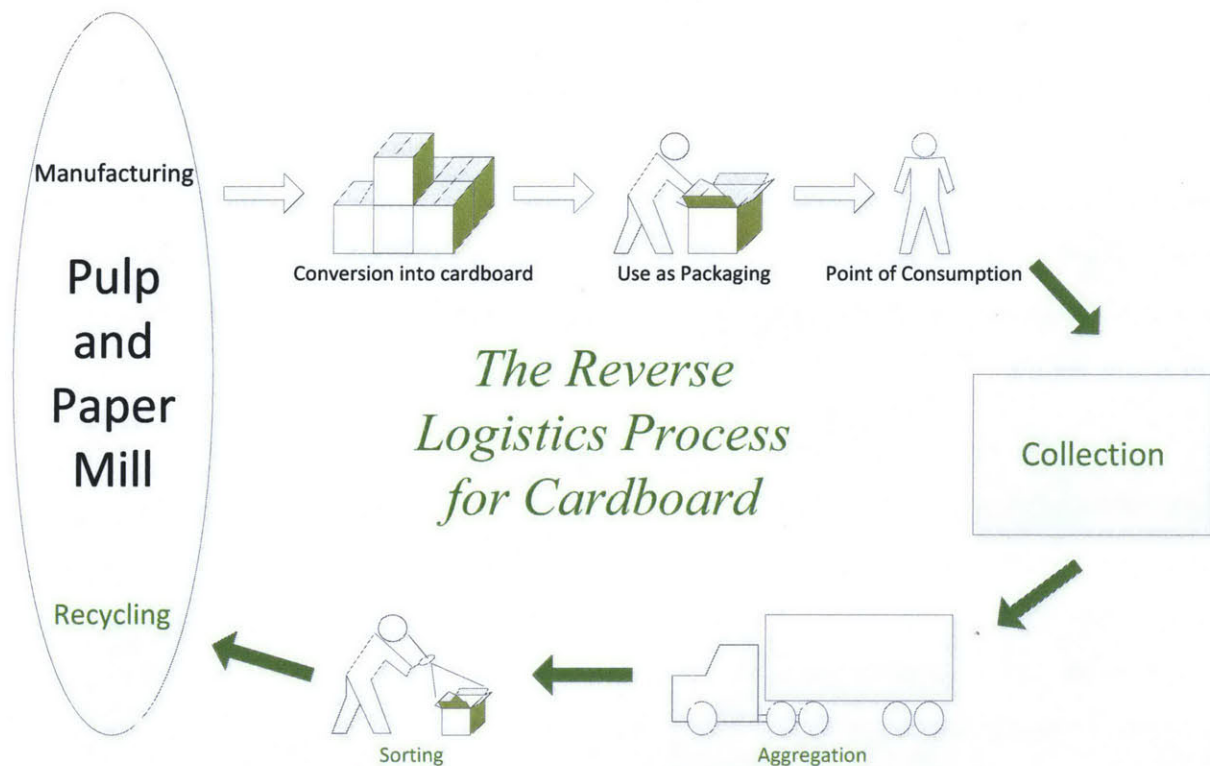


Figure 3: Activity Based Diagram, Forward and Reverse Logistics of Cardboard

A mature reverse logistics system with integrated collection systems and excellent consumer awareness can serve as a model for what is capable from reverse logistics metrics perspective. Collection rate is perhaps the most critical reverse logistics system metric. Though collection rate data specific to Dane County, WI is not available, the U.S. EPA lists a nationwide collection rate that can be thought of as the minimum likely collection rate for Dane County given that Dane County offers a premium collection system (curbside pickup) to its residents. This nation-wide collection rate is listed as 72%. This same EPA study lists the recycling recovery rate for cardboard at 85%.

The reverse logistics processes that have resulted from recent EPR mandates are generally less mature and are not supported by existing waste collection processes. Thus collection of this material, e-waste for example, becomes a challenge for the reverse logistics model. Note that the municipality plays a major role in the collection of cardboard material, municipal participation is not a given in the most recent EPR mandated collection systems. Instead, retailers often serve as the collections points, meaning there is less convenience for the consumer and thus a smaller likelihood that they may participate in the reverse logistics network. Consumers must decide whether or not to transport items to the retailer, or simply dispose of

them by other means, typically municipal landfill collection. One factor that can influence collections is the degree to which consumers must make a dedicated trip to the collection area. Offering collections in a location that the consumer may frequent for other purposes, will generally increase collection volumes. In some reverse logistics networks, the collections are done through a municipal drop-off site, and thus the trip to the drop-off site is completely dedicated to the purpose of recycling. These collection systems do little to build consumer collection volumes.⁸

The other primary difference between existing, well established, and profitable reverse logistics networks versus recently mandated EPR based systems is the extent of network development. Developing reverse logistics networks will have fewer aggregation points, sorting facilities, recycling locations, and re-introduction points into the forward supply chain. In this way, well developed, high volume reverse logistics networks enjoy what can be considered as economies of scale in comparison to developing networks.

3.4 Life Cycle Analyses (Influential studies)

The most recent and most influential large scale Life Cycle Analysis (LCA) performed in the battery industry was done by Olivetti, Gregory, and Kirchain of MIT and focused specifically on Alkaline batteries. However, there have been other influential studies, including a study performed specifically on Lithium Ion batteries by L. Gaines, J. Sullivan, A. Burnham, and I. Belharouk as well as a 2006 comprehensive LCA completed in support of the EU battery directive which was conducted by a firm known as Environmental Resource Management (ERM). The aforementioned LCA, conducted by ERM, is focused primarily on the United Kingdom but contains many energy utilization metrics and other pieces of information which will be of aid in the analysis presented in this paper.

The Alkaline LCA study limited its scope to the USA and focused on end of life impacts of the alkaline batteries. Comparisons were made between landfilling the batteries as well as collecting and recycling the batteries via various available collection and recycling methods. These comparisons were made in terms of Cumulative Energy Demand (CED) and Global Warming Potential (GWP), as well as ecosystem quality and human health metrics. The basic

⁸ (Smith, 2013)

finding of the study is that the collection and recycling of alkaline batteries may be advantageous from an ecosystem quality and human health perspective. However, regardless of the collection and recycling methods chosen there is likely a negative environmental impact, in terms of CED and GWP, to the collection and recycling of alkaline batteries in the USA. Despite this, the study concludes with several recommendations that may alleviate this environmental impact. One such recommendation which, if implemented, would have impact on this analysis is the recommendation for additional recycling locations (specifically electric-arc-furnaces) distributed throughout the USA to minimize the transport burden of the current alkaline battery recycling network flows. The results and recommendations of the Alkaline LCA have demonstrated enough promise that the US based producers of these batteries have formed their own organization to respond to the results of this study. The Corporation for Battery Recycling (CBR) is profiled in section 6.2.3 of this paper.

As with the alkaline LCA study, the Lithium LCA study was also completed in 2011. The executors of this LCA study represented both the Center for Transportation research as well as Argonne National Laboratory. The focus of the Lithium LCA was on the impact of electrification of the US transportation system and the resulting volume increase of lithium ion batteries. The LCA study compares a few different recycling methods and offers a valuable insight; Electrification of our vehicle system may offer battery recyclers with powerful economies of scale, improved standardization of form factors, and perhaps some method of design for recyclability (product features that may enable machine sorting). Even in the absence of these forecasted improvements, the current LCA results for li-ion batteries are favorable. This is largely due to the ability of the recovered materials, primarily cobalt, to be re-introduced into the Lithium battery production process and thus support a closed-loop supply chain. It is estimated that the generation of lithium battery raw materials from recycling, rather than virgin sources, reduces material production energy by up to 50%⁹. While the alkaline LCA drew immediate response and action from producers and stakeholders, the lithium LCA was focused on a future state, and thus there appears to be no immediate response from producers, recyclers, and other stakeholders.

⁹ (Gaines, Sullivan, Burnham, & Belhararouak, Life-Cycle Analysis of Production and Recycling of Lithium Ion Batteries, 2011)

The 2006 LCA completed by ERM in support of the EU battery directive is the most comprehensive battery LCA conducted to date. This LCA touches all major battery chemistries and the multiple end of life scenarios that may affect each chemistry. It is particularly helpful to the researcher due to the level of detail providing and the transparency with which each of the recycling processes are evaluated. Many of the energy utilization metrics that are inputs to the analysis that follows are taken from this LCA. Another feature of this LCA that makes it unique and useful to the researcher is the extensive cost analysis performed. Though the basic conclusion of the study is that battery recycling is advantageous from an environmental perspective, the study also details that great increase in costs associated with this reverse supply chain in comparison with existing landfill practices.

4 Methods to evaluate recycling systems

4.1 Holistic Quantitative Measures

As more and more governments introduce legislation to mandate reverse logistics processes, it is important that metrics exist to evaluate both the efficiency and effectiveness of these processes. Critical measures that have been used to evaluate reverse logistics and recycling processes holistically include carbon footprint (GWP), Cumulative Energy Demand, cost measures such as cost/ton and net profit/cost, environmental measures such as ecosystem quality and human health, and public awareness measures such as dollars spent on advertising.

A life cycle analysis study is critical in determining the environmental viability of the reverse logistics system. Such a study may include GWP, CED, and environmental factors analysis. A GWP study will determine the amount of greenhouse gasses (CO₂, CH₄, N₂O) emitted in the reverse supply chain. As the overall intent of many reverse logistics systems are based on environmental factors, ensuring the environmental benefit exceeds the environmental toll of the program is critical. Perhaps, nowhere is the importance of life cycle analysis more critical than in the potential launch of a reverse logistics system for Alkaline batteries in North America. As stated earlier, the LCA documented by Olivetti, Gregory, and Kirchain has driven much follow-up on the part of producers and much momentum within other stakeholders of the reverse logistics system. Of course, in cases of hazardous material recovery, the importance of carbon footprint and cumulative energy demand may be minimized.

Specific environmental measures that may be considered include ecosystem quality and human health. These metrics are both defined in the “Eco Indicator 99” method for the evaluation of life cycle impact. Damage to ecosystem quality is a measure of the loss of species over a certain area, during a certain time. Damage to human health is a measure of the number of years of life lost and the number of years lived disabled. These are combined as Disability Adjusted Life Years (DALYs)¹⁰. Though each of these metrics is quantitative in nature, it is up to the stakeholder groups to determine the relative importance of these measures vs. other considerations in the reverse logistics networks. Thus, subjectivity cannot be eliminated from the discussion.

¹⁰ (Ministry of Housing, Spatial Planning and the Environment, 2000)

Cost is another factor that determines the viability of the reverse logistics system. Though producers, consumers, and even local governments are willing to bear some costs in the support and execution of reverse logistics – there is a limit to what stakeholders are willing to invest. To the extent that a reverse logistics system can actually deliver tangible value from a purely cost perspective, the easier and speedier it will be to implement the system. A metric such as cost per ton is utilized to understand the cost of producing materials within the reverse supply chain for re-introduction into the forward supply chain. This cost per ton is then compared to the cost per ton of virgin materials. It is somewhat complex to derive true cost per ton metrics, because there are many players within the reverse logistics system. This includes many collection sites, sorters and recyclers as well as differing purchasers of recovered materials.

While collection rate is discussed in the next section as a sub-process measure, general awareness of the reverse logistics system is considered to be more holistic in nature. Though awareness is difficult to quantify, some EPR programs have tracked total advertising dollar spending as an indicator of awareness. Awareness may also be assessed through surveys administered to the target population.

4.2 Critical sub-process measures

A few basic, high level processes exist within nearly all reverse logistics systems. These processes, as shown in the aforementioned figure 1 are collection, sorting, recycling/re-processing, and redistribution into the forward supply chain. Each of these sub processes, particularly collection, sorting, and recycling have specific metrics to determine their effectiveness. For collection, the primary effectiveness measure is collection rate. This is generally thought of as the proportion of product that is recovered as compared to the proportion of product which is sold for a given time period. A rudimentary formula for collection rate is shown below:

$$\frac{\text{Amount of product collected (tons)}}{\text{Amount of product available for collection (tons)}}$$

There is some disagreement regarding the appropriate value for denominator in the above equation. While producers would like the collections in a certain time period to be relative to the

amount of product distributed in the same time period (amount of product available for collection would then be equal to amount sold), critics contend that the determining the number to use in the denominator is not that simple. They point out that the true amount of product available for collection must account for product already in the hands of consumers and consider the life span of these products.

Research conducted by the Product Stewardship Institute poses that differing calculation methods can have a widely varying effect on the observed collection rates. Citing battery collection rates in Canada vs. EU countries, they note reported collection rates between 2-6% in Canada vs. rates of 54% and 34% in Belgium and France respectively¹¹. In Canada, the collection rate calculation attempts to account for product already in the hands of consumers, while the EU collection rate calculation is simply driven by current sales. Despite the debate regarding the appropriate calculation of the collection rate metrics, there is general agreement that the true value add comes from tracking this metric (in any form) and setting improvement targets. So long as the method of collection rate calculation is explicitly communicated and believed to be sound, if not totally accurate, by the majority of stakeholders¹².

While the collection rate is the dominant metric to determine the effectiveness of a collection system, there are sub-metrics that should be tracked and understood to help improve collection rate performance. These metrics relate primarily to convenience and aim to measure three things, the total number of collection sites, the general proximity of the population to these collection sites, and the degree to which a trip to a collection site is dedicated to the recycling activity.

In many reverse logistics systems such as those for e-waste, general recycling, and batteries, waste is collected in a non-homogenous fashion and must be sorted prior to introduction into the recycling process. The primary metric for evaluating the effectiveness of a sorting operation is accuracy, though there may also be throughput metrics such as capacity and sorting rate in order to balance material flows throughout the reverse supply chain. Depending upon the sensitivity of the recycling process, accuracy may be a critical component to the effectiveness of the reverse supply chain and may impact downstream recovery rates. In the

¹¹ (Product Stewardship Institute, 2012)

¹² (Linnell & Nash, 2009)

current North American reverse supply chain for batteries, a portion of the responsibility for accuracy is pushed upstream to the collection site via a fine structure for improper mixing of battery chemistries, though these fines are generally enforced only in situations of gross error and negligence¹³. As such, the need for sorting operations still exists. A study of EU battery sorting processes Ponce-Cueto, Blanco, and Ciceri of MIT finds that manual sorting operations are actually more effective than automated methods¹⁴. This is an important finding as it may have operational implications for sorting and recycling processes.

In recycling processes, the primary metric to determine effectiveness is recovery rate. Recovery rate is defined as the proportion of product recycled in comparison to the amount of product collected. A basic formula for recovery rate is shown below.

$$\frac{(\text{weight of parts reused} + \text{weight of parts recycled})}{(\text{total weight of waste collected})}$$

This is not to be confused with the more holistic method of “recycling rate” which is defined as the proportion of product recycled in comparison to the amount of product available for collection. The recovery rate metric has been used successfully to drive producer innovation in many ways. This includes an emphasis on design for disassembly and an influence on raw material selection. There are many secondary metrics for recycling processes that directly relate to environmental considerations, these may be metrics such as amount of material kept out of the landfill system and amount of hazardous waste recovered. It is also important to note, that though qualitative in nature, an important success factor that must be considered when evaluating recycling systems is the purity and or reusability of the materials recovered. In some cases, though materials are recovered, they do not reach the purity or quality of virgin materials and thus cannot contribute to a closed loop supply chain. This is often the case in the battery reverse supply chain, lithium and zinc metal being primary examples.

Table 1, on page 27, is a summary of metrics commonly used to evaluate reverse logistics processes.

¹³ (Leimbach, 2012)

¹⁴ (Ponce-Cueto, Blanco, & Ciceri, 2012)

Table 1: Commonly used metrics to evaluate reverse logistics processes

Category	Holistic	Collection	Sorting	Recycling
Primary Metric	GWP or CED	Collection rate	Accuracy	Recovery Rate
Secondary Metric	Cost per ton	# of collection points	Total capacity (tons)	Material diverted from landfill (tons)
Secondary Metric	Advertising dollars spent	Proximity to collection points (average distance)	Throughput (tons/unit time)	Hazardous waste recovered (tons)
Secondary Metric	Ecosystem Quality or Human Health	Degree of Trip Dedication	NA	GWP or CED of the Recycling Process

4.3 Incentives

4.3.1 Manufacturers

Though much of the incentive from a manufacturer perspective is regulatory compliance related, Daugherty, Autry and Ellinger list 6 specific incentives for manufacturers to operate effective reverse logistics networks¹⁵. These are shown below:

- Environmental regulatory compliance
- Improved profitability
- Recovery of assets
- Reduced inventory investment
- Cost containment
- Improved customer relations

While all of these are true incentives for a manufacturer to implement reverse logistics, the Japanese industry experience as a first mover in this area has uncovered additional manufacturer incentives. These include R&D improvements that result from the design for disassembly process as well as materials development that results from focusing on the ability to re-use and

¹⁵ (Daugherty, Autry, & Ellinger, 2001)

recycle materials¹⁶. It is believed that the many small improvements in these areas can lead to sustainable competitive advantage for the firms who are able to patent and protect their innovations.

4.3.2 Consumers

Consumer incentive, though primarily driven by personal environmental concerns, can also be influenced by the particulars of the reverse logistics system. Incentives used to drive consumers to utilize reverse logistic systems include deposits, pre-paid disposal fees, legal requirements, and convenience. Deposit systems are widely used in classic reverse logistics systems such as those in place for glass and aluminum beverage containers. These deposits not only incent the actual consumer of the product, but other individuals and organizations are also incented to collect the waste and realize the deposit if the product is not disposed of properly. Pre-paid disposal fees are those fees that are collected from the consumer at the time of purchase. While these fees may not account for the total cost of the reverse logistics system, they help to offset this total cost and incentivize the consumer to return the item to the reverse supply chain at the end of its useful life. In this case, the consumer generally feels as if they have paid for a service and may actually go out of their way to utilize the service since they feel they are owed. The state of California has implemented such a system, the Advanced Recovery Fee (ARF), which was implemented in 2003 to aid in electronic waste recovery and appears as a separate line item on consumer purchase receipts¹⁷.

Legal requirements to recycle are generally put in place by municipalities and local governments. In these cases consumers are incented to participate in order to maintain compliance with local laws. These legal requirements tend to be more successful if they do not pass a direct cost burden to the consumer. It is important to note that consumers can also be disincentivized to utilize reverse logistics systems. Often, this occurs when the consumer bears a cost burden to utilize the reverse logistics system at the end of a products useful life. A consumer may be required to purchase a permit or pay a fee to appropriately dispose of an item. All too often, in these cases, the consumers will find other means to dispose of the items that are not as environmentally sound as the established reverse logistics system. Ogushi and Kandlikar

¹⁶ (Ogushi & Kandlikar, 2007)

¹⁷ (Sachs, 2006)

in their article regarding Japanese EPR laws describe the efforts that consumers will expend to avoid the fees associated with automobile disposal. In this case, as in others, consumers will knowingly take actions deemed “illegal” if no real enforcement, oversight, or consequence exists.

Finally convenience is a big factor in consumer utilization of collection programs. Generally speaking, people prefer to do the right thing. If doing the right thing is also convenient, then a major barrier toward utilization of reverse logistic systems is removed. The best examples of this are municipalities that have provided plastic, cardboard, and or metals recycling capabilities to consumers along with their household waste collection. In these cases, the amount of post-consumer waste materials collected is believed to be significantly greater than the practice of asking the consumer to bring these materials to a centralized collection location.

4.3.3 Retailers

While Producers and Consumers may be thought of as the dominant stakeholders in any consumer product transaction, the retailer is nearly as critical of a stakeholder since they also derive a substantial benefit from the transaction. Municipalities and product stewardship organizations are keenly aware of this and actively seek retailers to be part of the reverse logistics solution. The most practical value that a retailer can add to a reverse logistics network is that of serving as a collection site. With multiple locations, and good proximity to the end consumers and thus the point of use for the product, retailers are able to add a level of convenience to the collections process that far exceeds a single centralized municipal collection point. Additionally retailers enable the consumer to bundle their trip with other necessary activities, thus reducing the degree of dedication for of the trip and lowering the overall GWP of the reverse logistics network.

From the retailer perspective, the benefits are two-fold. Firstly, retailers are able to meet the expectations of municipalities and product stewardship organizations at very little added cost to the business, and in some cases may actually profit from the collection activity. Programs such as Call2recycle, which are EPR based, assess no cost to the retailer for the processing the batteries that are collected, while Battery Solutions will actually pay the retailer for certain types

of consumer batteries (all chemistries except alkaline). Additionally, manufacturers may sponsor, in part, the retailer collection programs in areas where EPR legislation is active. Also, retailers generally do not centrally manage the recycling program, instead each individual retail location is able to send their battery collections directly to the recycling center. This reduces overall management overhead for the collection program from the retailer perspective¹⁸. Secondly, being a collection site enables the retailer to provide a genuine value added service to its customers, and may help to drive incremental new or repeat business. Perhaps the best example of a successful retailer collection program may be Best Buy, who maintain that their e-waste collection program is a self-funded initiative that actually returns a small profit to the retailer¹⁹.

4.3.4 Local government

Local governments are incented to implement reverse logistics systems for three primary reasons, preserving limited landfill space, passing waste collection and processing costs to other stakeholders, and to preserve public health. While there may a general belief that available landfill capacity is dwindling in the developed world. Research into U.S. landfill capacity finds differing thoughts regarding true landfill capacity. What cannot be debated however is that regardless of the overall landfill capacity in the US, there are many instances of acute shortages of landfill capacity at the municipal level. These shortages drive municipalities to find ways to route waste away from their landfills, particularly recyclable materials.

The reality of post-consumer waste disposal is that it requires municipalities to deal with a problem that they did not create. Post-consumer waste disposal is simply an externality that arises from the transaction between producers and consumers. As more and more municipalities recognize their role in paying for what is truly an externality, these municipalities seek to assess the costs of post-consumer waste disposal to those directly involved in the purchase and sale transaction. As municipal budgets tighten throughout the U.S., local governments seek to avoid costs and generate additional revenue streams. Enacting EPR laws and assessing fees to direct disposal of certain post-consumer items is one method of meeting budgetary constraints while maintaining waste collection services.

¹⁸ (Sova, 2013)

¹⁹ (Aston, 2102)

Government at all levels has a basic responsibility to preserve public health. This especially critical in the disposal of chemical and electronic waste, which contain many toxic materials. The European Commission has noted that landfills are not watertight, and “a certain leaching of metals and chemical substances cannot be excluded”²⁰. Most battery chemistries, particularly secondary or rechargeable batteries, contain heavy metals. These include Lead, Nickel, Cadmium, and Lithium. When landfilled, these heavy metals can leach into soil or groundwater, and when incinerated they may enter the airstream. In either case, there is a negative effect on human health that can be measured by a variety of toxicity factors. The Battery Waste Management LCA of 2006 shows current landfill practices to have a much greater toxicity impact than any of the 9 recycling scenarios evaluated²¹. An obligation to public health forces both national and local governments to determine new methods to handle the ever changing waste stream. Reverse logistics systems present a viable solution from both an execution and cost perspective.

²⁰ (Sachs, 2006)

²¹ (Fisher, Wallen, Laenen, & Collins, 2006)

5 Battery Chemistry and Recyclability

5.1 Alkaline

The alkaline battery reverse supply chain is under-developed in comparison to other battery chemistries. This may be due to a number of factors such as perceived environmental impact, value of materials recovered, and the inability to reuse, refurbish or remanufacture this battery type. The life cycle analysis (LCA) on alkaline batteries conducted by Olivetti, Gregory, & Kirchain concluded that it was not economical to recycle alkaline batteries unless the recycling process can go beyond recovering only zinc from the batteries²². These factors contribute to the initial challenge of basic post-consumer waste collection for this type of battery. Figure 4, shown below, demonstrates a basic reverse supply chain for Alkaline batteries. Note that in this depiction, the reverse logistics network is able to recover more than just the zinc metal used in the battery.

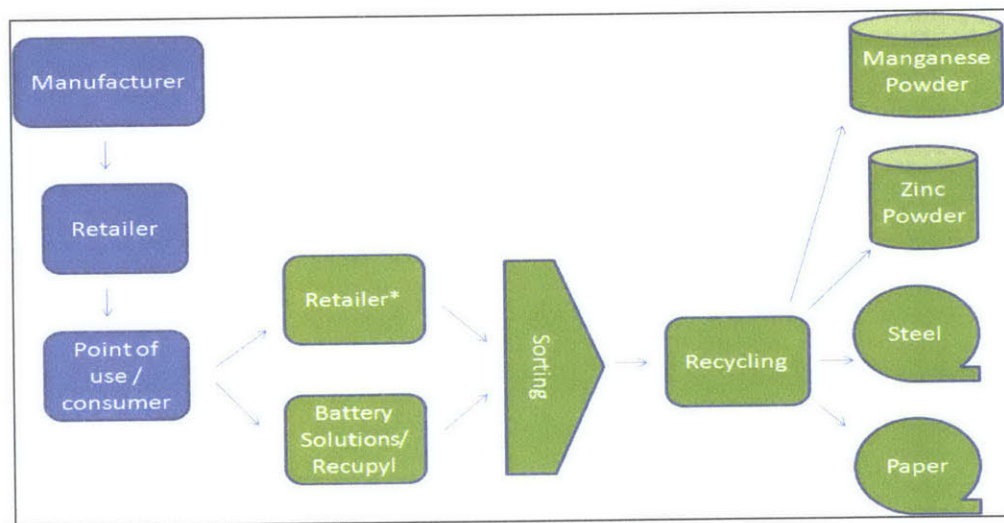


Figure 4: Reverse supply chain for Alkaline Batteries

The initial challenge with this battery chemistry is collection. The major established battery collection system in the USA “Call2recycle” is organized only to accept rechargeable battery types. Thus one of the most readily available collection systems is not available for this battery chemistry. Some specialty retailers, such as “Batteries Plus”, will collect alkaline batteries but do so at a cost to the consumer. Other collection systems such as Battery Solutions and Recupyl enable consumers to send their batteries directly to the recycler via paid postage along with a handling fee. The current structure creates a disincentive for the consumer, because the other

²² (Olivetti, Gregory, & Kirchain, 2011)

option is to throw these batteries out with other household trash. This is consistent with the guidance provided by the largest U.S. based manufacturer of these batteries. The following excerpt is taken from the Duracell website: Alkaline batteries can be safely disposed of with normal household waste...Proven cost-effective and environmentally safe recycling methods are not yet universally available for Alkaline batteries²³.

A second challenge, which is perhaps the cause of the first challenge, is to perform the recycling process at a profitable rate. While two primary recycling processes exist in North America, pyrometallurgical and hydrometallurgical, neither process can be done profitably without assessing some burden to the end user. The outputs of the pyrometallurgical Alkaline recycling process are Zinc and Zinc Oxides and are not able to be re-used as battery chemicals. Instead, the Zinc will go to the steel industry and the Zinc Oxide will be utilized by the rubber industry²⁴. The outputs of the hydrometallurgical recycling process, primarily zinc and manganese, are sent to the fertilizer industry at a profit to the recycler (profit meaning revenue that exceeds shipping costs). Though plastics, steel and paper are also recovered from the hydrometallurgical process, these cannot be re-introduced into the forward supply chain in a profitable manner²⁵. Unless more profitable alternatives are found, it may be difficult to organize a successful reverse supply chain for this battery chemistry.

5.2 NiMH

Though Ni-MH batteries are generally perceived to have a low overall environmental impact, a financial incentive exists to recover these batteries. This incentive is in the form of the nickel metal that can be recovered and then re-processed into battery materials. In this way, the Ni-MH battery chemistry is able to support a partial closed loop supply chain. In addition to the nickel metal, slag materials for the concrete industry and steel may also be recovered. There may also be positive environmental impact due to the incineration of the Ni-MH electrolyte chemicals and the cleaning of subsequent gases.

Ni-MH batteries are recycled through a pyrometallurgical process, in which a smelting furnace is used to incinerate the batteries, the waste gases are scrubbed and the resulting molten

²³ (Moquet, 2011)

²⁴ (Smith, 2013)

²⁵ (Sova, 2013)

metals are recovered. Though there are many variants of the pyrometallurgical process due primarily to the different chemistries available, a basic diagram of the process for Nickel recovery is shown in figure 6

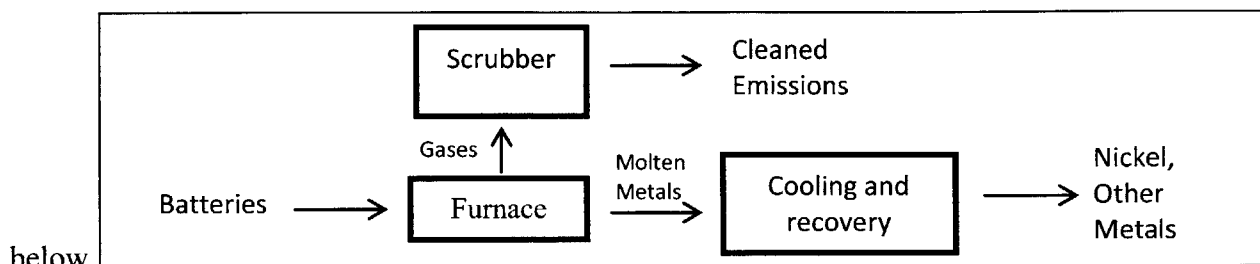


Figure 6: Pyrometallurgical recycling process - Nickel

5.3 Li-ion

Li-ion batteries can be 100% recycled. The recycled products are usually nickel salts, cobalt salts and lithium salts. According to available literature, nickel and cobalt recovery makes economic sense, but lithium does not as it is fairly abundant, with relatively low prices for virgin raw material²⁶.

Due to the complexity of the recovery processes, only a few companies in the world are able to handle Li-ion battery recycling. Of these companies, Call2Recycle works with Toxco and Xstrata, which have facilities to recover Cobalt and Nickel from Li-ion batteries, with the rest of the materials being recycled as slag for use in construction. In addition, Toxco is the only recycling facility that is able to extract lithium during the recycling process, and it does so by using a patented low temperature process²⁷. Other facilities around the world that are able to extract lithium salts from Li-ion batteries are Recupyl, Battery Solutions Inc and Umicore (Belgium). Figure 7, shown on page 35, illustrates the Li-ion recycling process for Toxco²⁸.

²⁶ (The Lithium Recycling Challenge, 2011)

²⁷ (Cardarelli & Dube, 2007)

²⁸ (Gaines, Sullivan, Burnham, & Belhararouak, Life-Cycle Analysis of Production and Recycling of Lithium Ion Batteries, 2011)

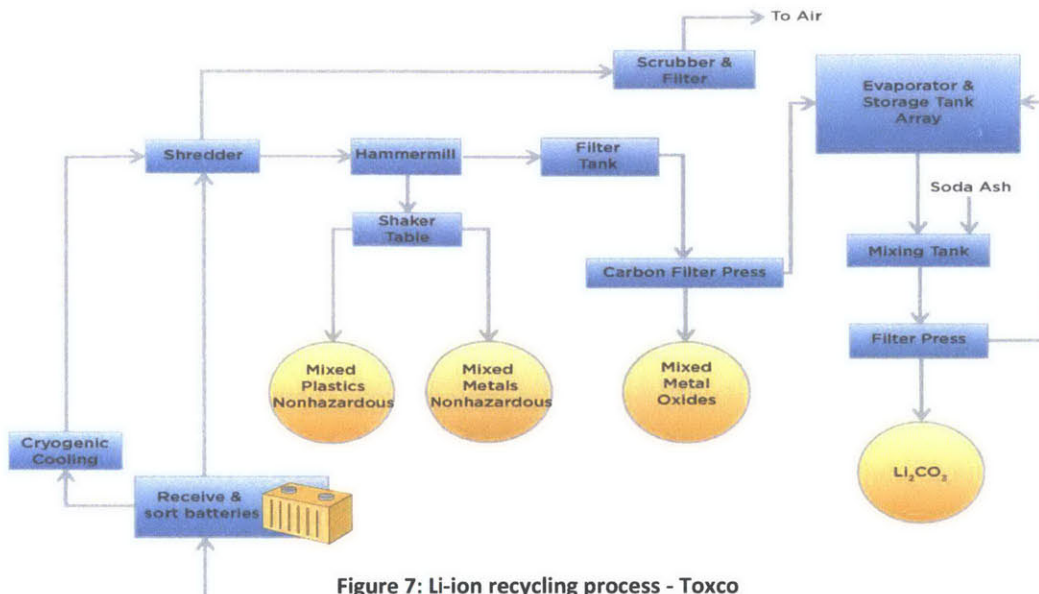


Figure 7: Li-ion recycling process - Toxco

(Gaines, Sullivan, Burnham, & Belhararouak, Life-Cycle Analysis of Production and Recycling of Lithium Ion Batteries, 2011)

5.4 Nickel- Cadmium

Due to the adverse health and environmental impacts of cadmium, diverse legislation has been introduced to both reduce the use of and recycle Nickel Cadmium (Ni-Cd) batteries. Ni-Cd should not be landfilled and must be carefully recycled. This is because cadmium, when landfilled, may leach into groundwater, and when incinerated may enter the air through smoke-stack emissions. In North America, as an EPA designated BDAT (Best Demonstrated Available Technology) facility, only Inmetco is able to provide Ni-Cd recycling services. Battery recycling at Inmetco is performed via an energy intensive pyrometallurgical process that consists of a rotary hearth furnace, metals pelletizer and smelter.

The primary items of value that are re-introduced into the forward supply chain from the Nickel Cadmium recycling process are Cadmium and a “remelt alloy” consisting of Nickel, Iron and Chromium. The Cadmium is of sufficient purity, 99.5%, that it can be re-used by battery manufacturers, thus supporting a closed loop supply chain for this material. The remelt alloy is used in the production of stainless steel. Figure 8 below is a high level schematic of the recycling process at Inmetco²⁹ with the battery specific recycling processes highlighted for reference.

²⁹ (Horsehead corporation, 2010)

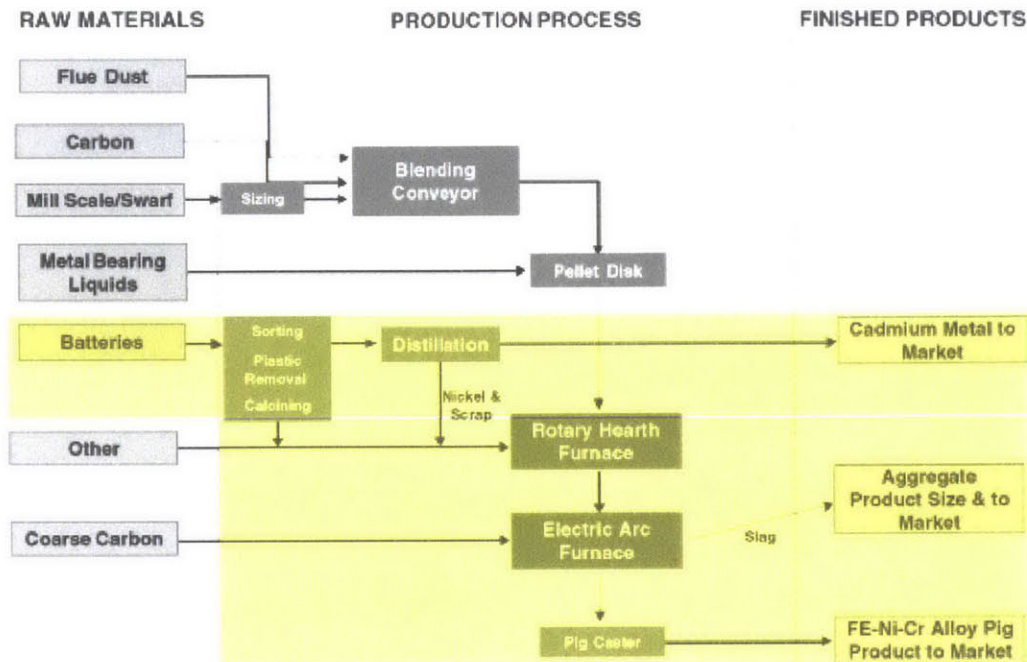
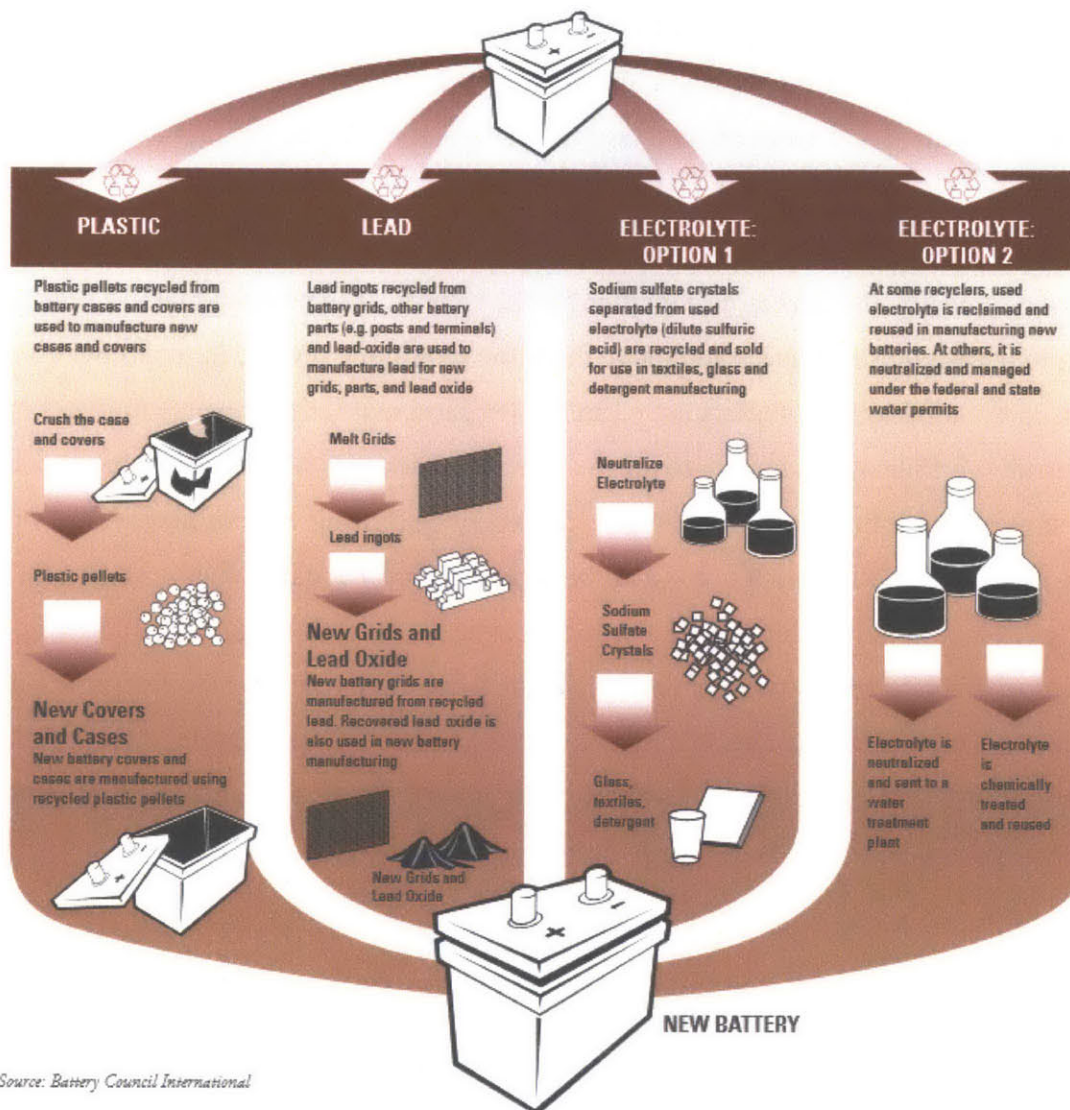


Figure 8: Ni-Cd recycling process - Inmetco (Horsehead corporation, 2010)

5.5 Lead Acid

The collection and recycling of lead acid batteries has been greatly successful. Though there are key differences between the supply chain systems, both forward and reverse, for lead acid batteries and household consumer batteries, the reverse logistics of lead acid batteries can still serve as a model of what can be achieved in a properly incentivized reverse logistics flow.

The primary components of a lead-acid battery are plastic, lead and electrolyte (dilute sulfuric acid). These components are mechanically separated in the initial stages of the recycling process, and then each is processed separately to create raw materials of sufficient quality that they may be introduced back into the forward supply chain. In fact, a critical success factor for the lead acid reverse logistics system is that it supports a closed-loop supply chain, wherein the recovered materials from the recycling process are re-introduced to the very same manufacturers and products. Figure 9 below, from the Battery Council International (BCI), shows that the plastic materials are pelletized, the lead materials are melted into ingots, and the electrolytes are processed in multiple ways prior to being re-introduced into the manufacturing process.



Source: Battery Council International

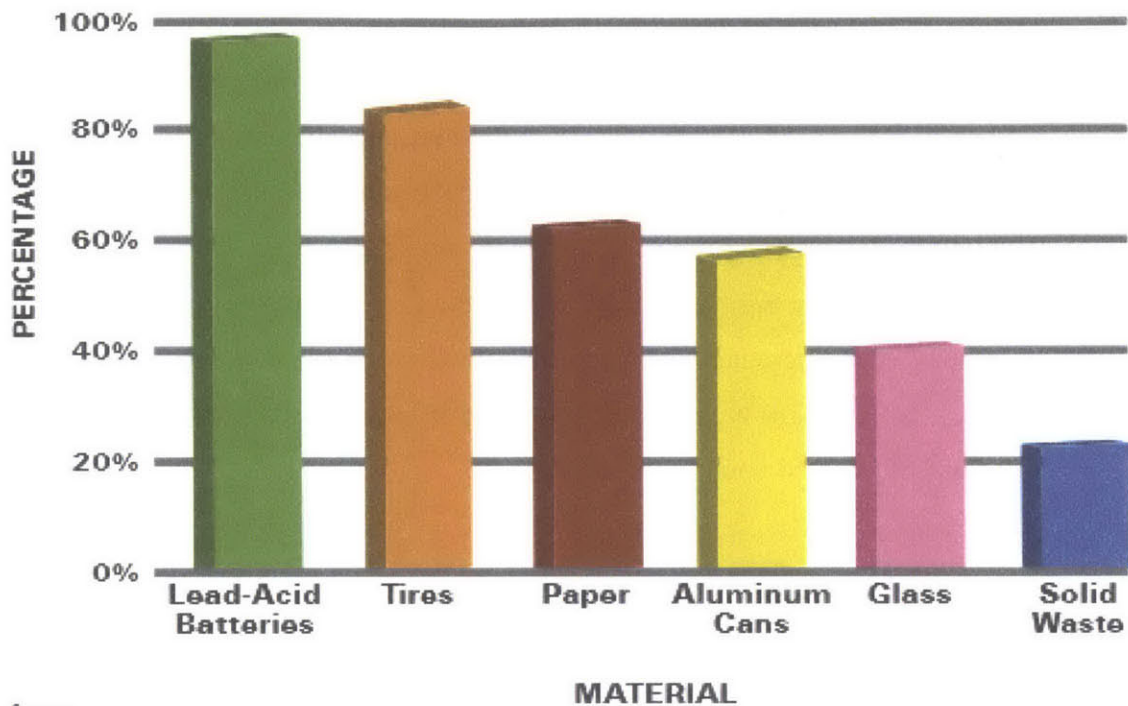
Figure 9: Lead-Acid recycling process (Battery Council International, 2013)

The process of transforming the spent lead into lead ingots that can be re-used is called smelting. This is a thermally intensive process in which the spent lead is melted to its molten form and impurities (in some cases materials deliberately added during the battery manufacturing process) are easily removed (due to differences in specific gravity) and near pure lead is recovered. Despite the immense thermal requirements to reduce these metals to their liquid form, the smelting and recovery of lead is still advantageous to the production of virgin lead from an energy consumption perspective, requiring approximately only 35 -40% of the energy needed to obtain lead from ore.

The unique advantages of the reverse logistics system for lead-acid batteries include the aforementioned closed loop supply chain, the fact that the product is primarily OEM and/or professionally installed and serviced, and lastly the real market incentives that exist for spent lead-acid batteries. The presence of a professional install network means that the consumer will generally not handle the battery at end of life, but rather this will be done by the professional installer who typically also serves as a retailer for the battery. The professional installer is organized to collect these batteries and move them forward in the reverse logistics network. Part of the reason the profession installers are organized to participate in the reverse logistics system is that they have a financial incentive to do so. The manufacturers will buy back the spent batteries at a price that fluctuates based on the market price of lead, which today is \$0.14 per lb. Given the range of form factors for lead acid batteries, this may equate to between \$1.50 and \$24 per battery³⁰. In addition to purchasing the spent batteries, the manufacturers will also cover the transportation costs for the batteries, in many cases collecting the batteries on the same trucks that deliver new batteries, thus minimizing empty truckloads. The cumulative effect of these unique advantages is shown in figure 10 below, where the collection rate of lead acid batteries in the United States is shown to exceed many commonly recycled items.

³⁰ (Leimbach, 2012)

Recycling Rates - Percentage of Reclaimed Materials



Source:
Smith Bucklin Market Research and Statistics Group (2011 National Recycling Rate Study)
The Rubber Manufacturer's Association (2009 tire recycling rates) 10/2011
The American Forest & Paper Association (2010 paper recycling rates) 04/2012
The Aluminum Association (2010 aluminum recycling rates) 06/2011
Glass Packaging Institute (2010 glass recycling rates) 04/2012
Environmental Protection Agency (2010 solid waste recycling rates) 12/2011

Figure 10: Recycling Rates for commonly reclaimed materials

6 Overview of Battery Recycling in North America

6.1 Business Ecosystems

The business ecosystem for the consumer battery reverse logistics network is made up of producers, retailers, recyclers and the companies who re-introduce the products of the recycling process to the forward supply chain. A major theme of the business ecosystem is “co-opetition”, as firms in the producer and recycler rungs are currently working together for a variety of reasons. Figure 11 presents the business ecosystem for the reverse logistics network.. It is important to note that, while there is no cooperation between retailers, there is also limited cooperation within retailers. This has an overall negative effect upon the supply chain which will be discussed and elaborated upon in this thesis.



Figure 11: Business ecosystem – consumer battery reverse logistics network

Among the battery producers, there is a shared realization that consumer battery recycling will likely be legislated throughout North America. Having seen extended producer responsibility systems effect their businesses in certain parts of Europe, the major primary battery producers in North America have engaged in cooperation to create and shape their own battery collection and recycling systems. This cooperation is through an organization called the

Corporation for Battery Recycling (CBR), and is further detailed in section 6.2.3 of this paper. A second producer organization, the Rechargeable Battery Recycling Corporation (RBRC) aligns the manufacturers of rechargeable batteries. The RBRC has established the Call2Recycle organization which is profiled in section 6.2.2 of this paper.

Among the recyclers, the cooperation is mainly due to recycling capabilities, and this has an effect on the logistics flow of the reverse supply chain. Inmetco specializes in the recycling of Nickel based battery chemistries (NiCd, NiMH), while Battery Solutions specializes in the recycling of Alkaline batteries, and Toxco specializes in the recycling of Lithium-ion batteries. Despite these areas of specialization, each of these recyclers offers holistic (all chemistries) battery recycling to its customers. This results in many cross-flows of materials between these three competitors. Since there is no competitive advantage in the holistic (all chemistry) consumer battery recycling space, opportunities exist for third party organizations who would seek to sell holistic recycling to customers and then use a combination of these three recyclers to meet the needs of their customers. Thus, these organizations provide no actual recycling services, though they may aid in the collections of batteries to be recycled. Though not mentioned in the business ecosystem shown above, the primary organizations applying this business model include Call2Recycle, CBR, Waste Management, and Veolia.

6.2 Organizational Profiles

6.2.1 Battery Solutions

Battery Solutions, established in 1971, is a for-profit recycler of consumer batteries and electronic waste. Currently, Battery Solutions is supporting the U.S. market only. The primary business model of battery solutions is to provide battery recycling “kits”, essentially shippable collection points (cardboard boxes, plastic pails, etc...), for residential, commercial, and municipal use. Additionally, Battery Solutions also has a “bulk” battery recycling program for retailers and large municipalities who may wish to aggregate multiple collection points on their own and ship large quantities to Battery Solutions. For recycling at the “kit” level, battery solutions will pass the costs of recycling to the organization that assembles the kit, be it a residential consumer, a corporation or municipal entity. At the “bulk” level, Battery solutions may actually pay the collector for the bulk batteries.

6.2.2

In contrast to Call2recycle (see section 6.2.2. for more details), Battery Solutions has its own recycling and sorting facilities, in fact it has two such facilities, one each located in Arizona and Michigan. All recycling is done at the Michigan facility in partnership with Recupyl, while the Arizona facility serves as a regional sorting and aggregation facility. Another contrast with Call2recycle is the ability of Battery Solutions to recover all major components of the alkaline battery in their recycling process. Through their partnership with Inmetco, Call2Recycle sends all their battery collections to Inmetco's Elwood City, PA facility. This facility is able to recover only the Zinc and Zinc Oxide materials from the alkaline batteries. Another important contrast with Call2recycle is in reporting. No public information is available regarding Battery Solutions actual collection amounts or company financials. For this reason, it is difficult to assess a cost to their reverse supply chain.

Call2Recycle (a.k.a. RBRC)

The Call2Recycle organization was established in 1994 by the Rechargeable Battery Recycling Corporation (RBRC). It focuses on the collection and transport of all battery types (Primary and Rechargeable), and operates its collection service solely within North America (United States and Canada). Figure 12 details the 2011 collection amounts for the Call2Recycle network.

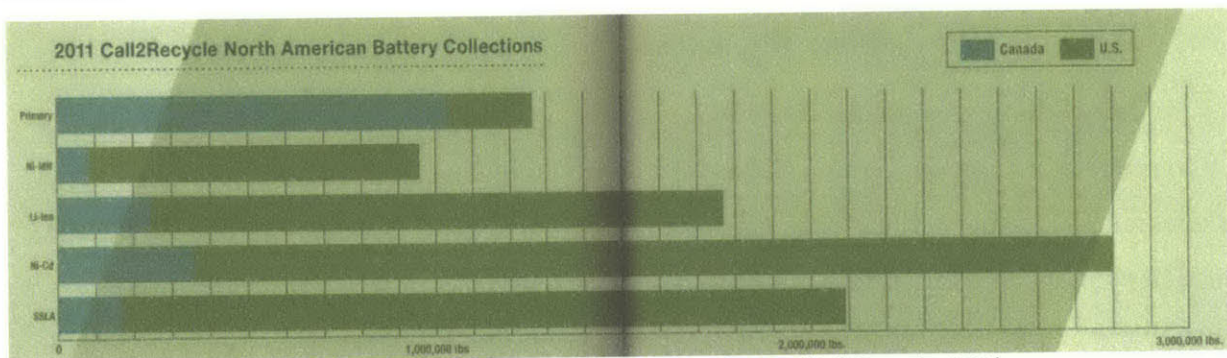


Figure 12: Call2Recycle collection volumes (Call2Recycle, 2011)

The above diagram accounts for a total of 7.6 million pounds of batteries collected by call2recycle in 2011. These batteries are collected through various municipal and retail partnerships, most notably Radio Shack, Best Buy, Office Depot, and Staples on the retail side and the provinces of Manitoba, Quebec, and British Columbia on the municipal side. The municipal programs encompass all battery types, while the retail programs generally focus on rechargeable batteries only. This explains why primary battery collection in Canada

far outpaces that which is done in the US. Call2recycle has made similar efforts to partner with states in the U.S., through proposing legislation that would require recycling at the municipality level in both Washington State and New York. The Washington State proposal was not ratified primarily due to reasons of program cost³¹, while the New York legislation has been ratified but has not yet been implemented³².

The operating mode for call2recycle is one of Extended Producer Responsibility. In the USA, manufacturer’s may voluntarily enter into the call2recycle program and are incented to do so by the ability to utilize the RBRC/call2recycle seal on their products and the resulting positive effects of this “green” affiliation. Additionally, the actual amount of recycled product for each manufacturer will be reported back to the manufacturer, thus the individual manufacturer recycle rate will be known – this is a helpful metric for environmental stewardship purposes. The manufacturer responsibility arises through funding of the program on a per cell collected basis. Figure 13 is an example of the fee structure (taken from the 2007 call2recycle contract)³³. While the entire fee structure is several pages in length, and encompasses all battery types, the Lithium-ion section is shown in figure 13 for illustrative purposes.

Total Voltage of Licensed Battery	A Quantity of Licensed Batteries	B Fee per Licensed Battery	A X B License Fee
Large Battery packs 8.1 volts and greater		\$0.02	
Small battery Packs 1.5 volts to 8 volts		\$0.01	
Retail “Round Cell” Less than 1.5 volts		\$0.0025	

Figure 13: Call2Recycle fee structure, Li-ion only (Leimbach, 2012)

³¹ (Leimbach, 2012)

³² (Smith, 2013)

³³ (Leimbach, 2012)

Since the manufacturer bears the cost of the call2recycle reverse supply chain, call2recycle is able to offer their collection services free of charge to the consumer and retailer. This creates strong incentives for both retailers and consumers to participate in the program. It is important to note that call2recycle functions as a collection organization only, and they maintain an important partnership with Inmetco a metals processing company in Ellwood City, PA. Since 1996, Inmetco provides sorting, smelting, and processing service to complete the battery recycling process for call2recycle. Inmetco does not support Lithium-ion battery recycling, and Call2Recycle utilizes both Toxco and Xstrata for this purpose.

Table 2 helps to highlight the important differences between call2recycle and Battery Solutions:

Table 2: Call2Recycle vs. Battery Solutions – important differences

Parameter	Battery Solutions	Call2recycle
Service Area	U.S.A	U.S.A and Canada
Structure	For-Profit	Non-profit
Own recycling capability	yes	No
Consumer cost	Incrementally reduced with increased collection volume	Free
Reporting	Hidden	Trasparent

6.2.3 Corporation for Battery Recycling (CBR)

The Corporation for Battery Recycling (CBR) is a non for profit entity which credits its founding to the results of the Alkaline battery life cycle analysis published by Olivetti, Gregory, and Kirchain of MIT. This analysis helped to demonstrate the environmental viability of Alkaline battery recycling. The CBR consists of three founding members: Duracell, Energizer, and Panasonic. Founded in 2011, the stated mission of CBR is to create a national battery collection system that maximizes cost efficiency, continuously improves collection rates, and shares responsibility between manufacturers, producers, consumers/users, retailers, and government. In its initial year, the main achievement of CBR was in bringing together over 75 stakeholder groups in the area of consumer battery recycling for a “Battery Summit” with the stated goal of designing a standard system for household battery recycling. Figure 14 is a high-level diagram of the proposed system as featured on the CBR website.

BATTERY RECYCLING SYSTEM

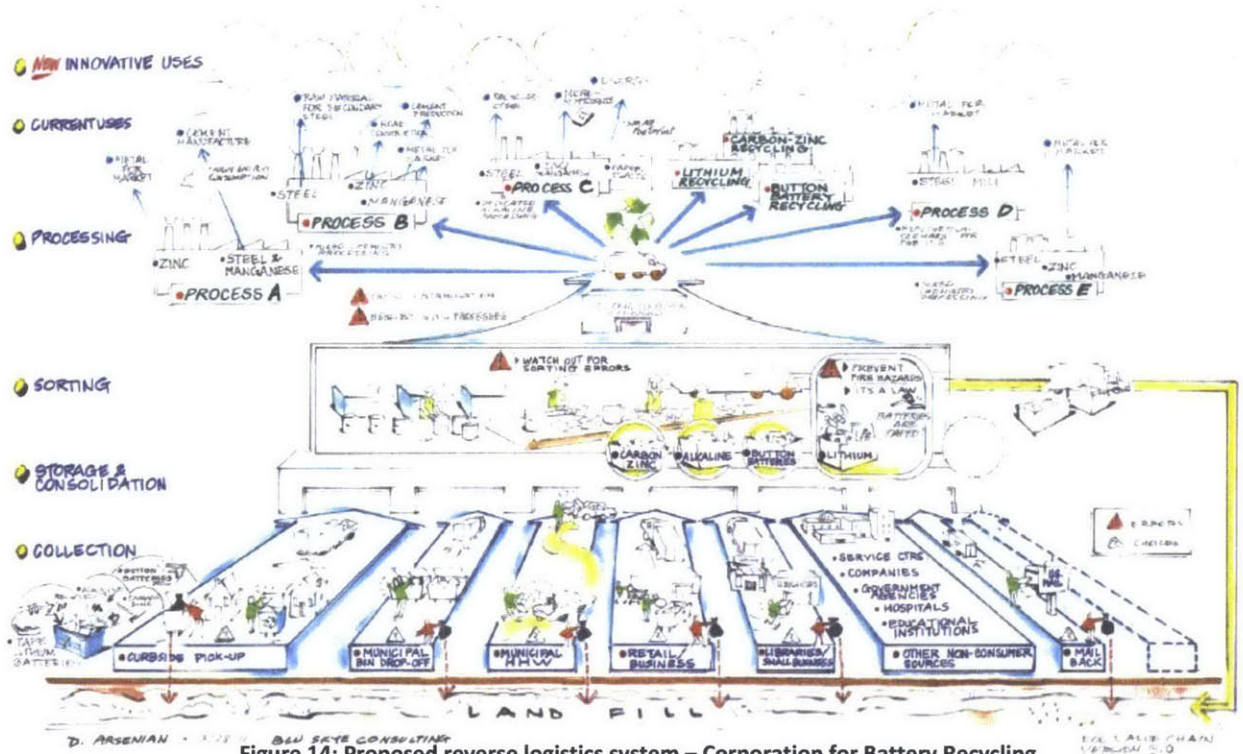


Figure 14: Proposed reverse logistics system – Corporation for Battery Recycling
(Corporation for Battery Recycling, 2011)

In 2012 the CBR became more aggressive in its efforts to launch a nationwide battery collection and recycling system and issued a request for proposal (RFP) seeking bidders who would provide this service. The RFP applied to all consumer/household battery chemistries and was officially seeking a “stewardship organization” to operate and maintain the nationwide collection and recycling program. Thus, the RFP could be satisfied by an organization that does not directly engage in the recycling of batteries, but rather administers the collection and recycling system and contracts with all parties involved. Likely candidates for the RFP included Waste Management and Veolia, as well as other in the waste disposal and environmental services industries. Due to recent (Q4 2012) changes in the CBR membership (Rayovac joined and then dropped out) the CBR has rescinded the RFP and is citing a lack of funding to pursue the program.

Despite rescinding the RFP, the three founding members of CBR remain committed to the organizations vision and will continue to operate CBR. Perhaps the primary function of the CBR in 2013 will be to continue the organizations 6 countywide “foundation projects”. These

projects are established in 6 counties within the United States, each with a sizeable metro area. In addition to gaining a better understanding of the feasibility of a collection system, these projects provide an important opportunity to assess the make-up of the batteries collected. Each project has been analyzed for battery composition by chemistry as well as by manufacturer. The results of these composition analyses are used in this thesis.

6.2.4 Inmetco

Established in 1978, Inmetco is a recycler of metals bearing waste focusing on the recovery of Nickel, Chromium, Iron, Molybdenum and Cadmium. Located in Elwood City, Pennsylvania (just outside of Pittsburgh) Inmetco maintains a strong focus on battery recycling though they are able to recycle other materials as well, such as stainless steel and metal waste from electroplating operations. Recycling is accomplished at Inmetco through first sorting the batteries and then introducing specific battery types to a pyro-metallurgical process for the recovery of valuable metals. Inmetco specialized in Nickel-Cadmium battery recycling and is the only facility in North America to process these batteries in a pyro-metallurgical process.

As with other battery recyclers, Inmetco offers a one stop solution for its customers through a “prepaid recycling program” in which consumers may purchase containers which they can then fill with all types of consumer batteries and return to Inmetco for processing. Additionally, Inmetco serves as the recycling partner of the Rechargeable Battery Recycling Corporation (RBRC) and their “Call2Recycle” program. Despite operating a holistic consumer recycling program and supporting another, Inmetco is incapable of recycling Lithium bearing battery chemistries. The recycling of these chemistries is supported through cooperation with other recyclers.

6.2.5 Recuypl

Recuypl has positioned itself as a technology leader in the field of battery recycling. Headquartered in France, Recuypl has operations in Poland, Italy, Spain, Singapore, and the US. Each of these operations is a joint venture with a local firm in which Recuypl has offered its technology as the recycling platform. The US operations will be discussed further as they are in-scope for this thesis. This US joint venture is with the aforementioned company, Battery

Solutions. Recuyl has provided technology for both Alkaline and Li-ion recycling, while Battery Solutions provides the collection network and sorting operations.

The key advantage that Recuyl offers in comparison to its competitors is a hydrometallurgical recycling process for both Li-ion and Alkaline batteries. This process is less energy intensive than the pyro-metallurgical processes in place with their competitors, and thus tends to do very well when studied from a life cycle analysis perspective. This is the very same process studied by Olivetti, Gregory, and Kirchain, in their Alkaline life cycle analysis. Figure 15 illustrates a high level diagram of the Recuyl Alkaline battery recycling process³⁴. Note that the drivers of this process are mechanical and chemical in nature, thus no energy is consumed in the creation of elevated temperatures. In addition to energy efficiency an onsite interview conducted with Jeremy Sova, Vice President of Account Management of the Recuyl/Battery Solutions joint venture indicated that there is essentially no waste from the alkaline process. All components generated from the breakdown of the Alkaline batteries are re-introduced into the forward supply chain.

³⁴ (Recuyl)

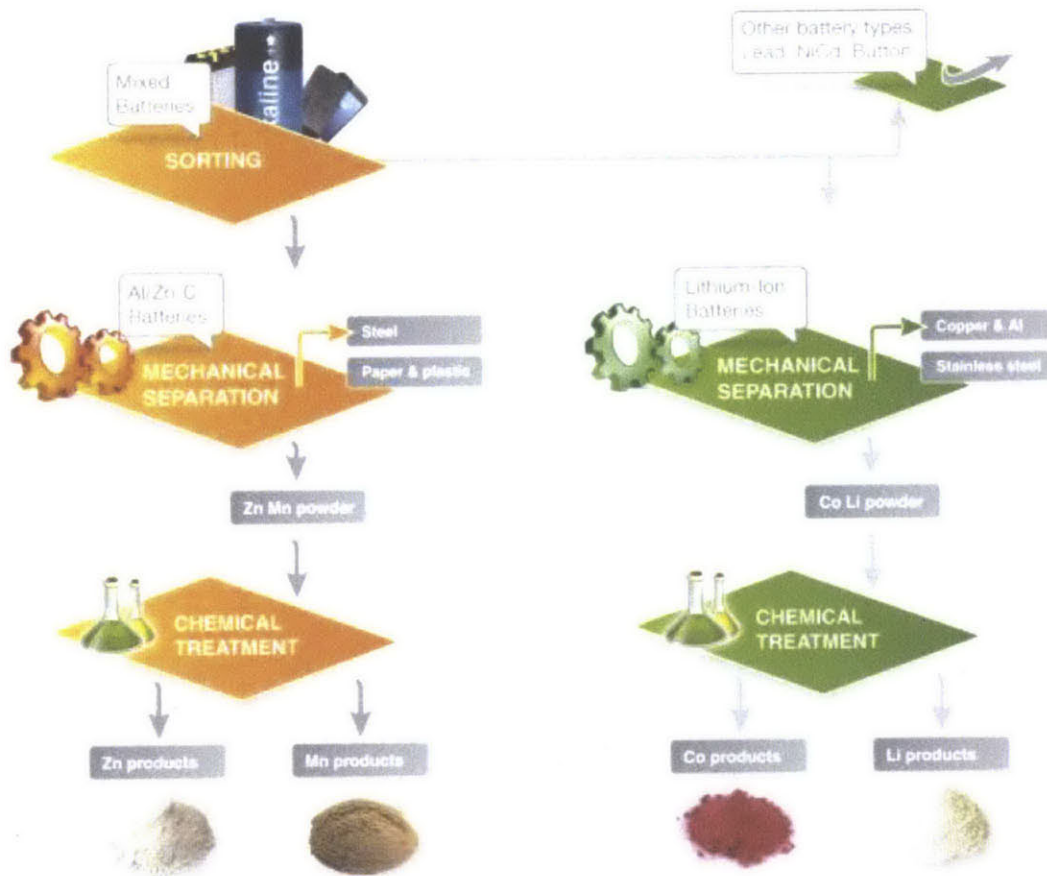


Figure 15: Battery recycling process - Recupyl (Recupyl, 2013)

6.2.6 Retailer Profiles - collections

Retailers play an important role in the collections of batteries for the reverse logistics network. This section will profile the retailer collection activities that support these networks. The retailers that will be compared and contrasted are Costco, a large “big box” retailer and BatteriesPlus, a specialty battery retailer.

Costco has an almost 500 store network within the USA. This network is supported by regional distribution centers that provide product to the stores. Battery collection occurs at the store level, with each store maintaining a small box for collections near the front of the store which is visible to and easily accessible for the consumer. This small battery box is then aggregated into palletized full Gaylord containers in the warehouse area of the individual store. When the Gaylord container is full, the batteries are sent to the recycler for processing. In this case, the Costco network has the ability to support a centralized aggregation of waste batteries, at their distribution center, but chooses not to do so, primarily for reasons of convenience. It is

easier if individual stores manage the battery collection and recycling program and centralized resources do not have to engage in managing the program. It is unclear if cost and/or other studies (GWP for example) have been carried out to determine whether a system of aggregating the store battery collections at the distribution centers would be advantageous. The study by Blanco, Ponce-Cueto and Ciceri, can be used to gain insight into this question. This study compares two level vs. 3 level reverse logistics networks and the conclusion of the study is that a two-level reverse logistics model is advantageous from a cost perspective when compared with three level reverse logistics networks³⁵. This would suggest that the Costco model of directly shipping from stores to central sorting facility, with no intermediate aggregation point may be the low cost reverse logistics model.

BatteriesPlus operates a 600 store retail network in the United States. These are specialty stores and the store footprint is quite small, primarily ranging from 1,600 to 2,200 square feet. Most stores maintain small box collection bins that are visible to and easily accessible for the consumer, similar to Costco. However some stores have removed these bins in favor of more highly profitable retail selling space. In these cases the store will recycle all battery types upon request. Regardless of the in-store collection methods, batteries are aggregated into separate, but still small-parcel containers in the back of the store. These collections are not aggregated into palletized quantities due to the lack of sufficient space inside the store to enable waste battery aggregation.

As with Costco, batteries are sent directly from the store to the sorting facility. However, in contrast to Costco, the option does not exist to easily aggregate batteries from multiple stores, since a third party logistics provider is used to supply the stores from a single U.S. warehouse facility. While per store collections volumes for both Costco and BatteriesPlus were not available, it may be argued that the per store collection volumes are much larger at Costco, owing to larger volumes of customer foot traffic than BatteriesPlus. Thus sending quantities of batteries to the recycler in anything less than a full Gaylord container may result in excessive handling of these batteries within the store. While, in the case of BatteriesPlus, the small-parcel shipments may result in the same frequency of shipments between retail location and sorting facility.

³⁵ (Ponce-Cueto, Blanco, & Ciceri, Designing Sorting Facilities in Reverse Logistics Systems, 2012)

6.3 Legislative Overview

While Europe is further along than North America in terms of battery recycling regulations and extended producer responsibility, in the United States, 32 states currently have laws that mandate some form of extended producer responsibility for any product. Extended producer responsibility is seen as the primary vehicle to mandate and/or support product recycling efforts. Of these 32 states, 9 of them have extended producer responsibility laws that apply specifically to batteries. The majority of these 9 states target Lead and/or Cadmium based chemistries for recycling, with only California and New York having broad enough legislation to apply to all rechargeable consumer batteries. Though both California and New York have comprehensive legislation mandating battery recycling, only California has enacted this legislation³⁶. This is likely due in part to age of this legislation, California's legislation was passed in 2006, while New York's legislation was passed in December 2010. However, the California Department of Toxic Substances Control shows significant recycling activity in the year following the legislation. This would suggest that New York has been slow to enact their legislation. A model of the rapid pace of recycling growth and the overall potential for battery recycling can be seen in the California battery recycling volumes since the inception of the program³⁷. Figure 16 is a graphical representation of these recycling volumes.

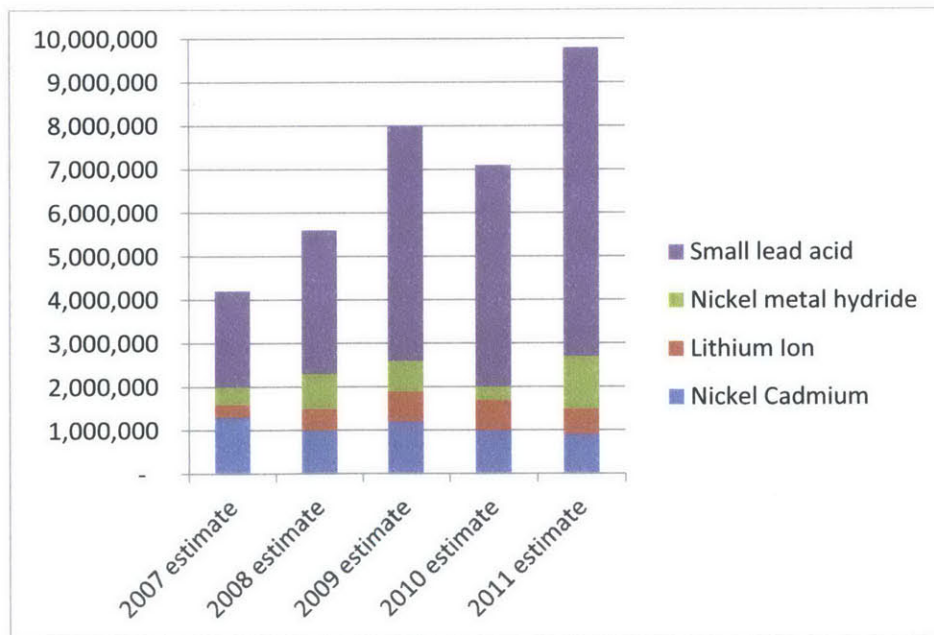


Figure 16: California battery recycling volumes

³⁶ (Leimbach, 2012)

³⁷ (California Department of Toxic Substances Control)

At the present time, there is no state legislation targeting Alkaline battery recycling, recall that these make up approximately 85% of the consumer battery waste stream. However, in Canada, the provinces have made significant strides toward mandating the recycling of both rechargeable and Alkaline batteries. The following provinces currently have regulations requiring battery recycling that are inclusive of Alkaline batteries: British Columbia, Manitoba, Ontario, and Quebec. Each of these laws passes some level of responsibility for the program to the producer and/or the retailer, and designates the use of an approved stewardship program or official recycling partner to carry out the actual collection and recycling program. See figure 12 in section 6.2.2 for a summary of the results of the Canada recycling program.

7 Evaluating the Current Reverse Supply Chain

7.1 Documenting current alternatives for Reverse logistics networks

The current reverse supply chain for battery recycling in North America is shaped by two dominant players in terms of collections, and “coopetition” between recyclers. The two firms who shape the collections landscape are the aforementioned Call2recycle and Battery Solutions. Though these firms work with a number of retailers and municipalities to provide physical collection points to consumers, both firms aggregate these collection points and then proceed upon differing reverse logistics material flows. Though these reverse logistics materials flows are different, they share the need for coopetition between recyclers in order to process the differing battery chemistries within the household consumer battery waste stream. The reverse logistics network for Call2recycle is shown in figure 17, while the reverse logistics network for Battery Solutions is shown in figure 18. Note that both networks include Inmetco as a recycling partner for Nickel-based battery chemistries. A map of North America showing the location of the sorting and recycling facilities is shown in figure 19

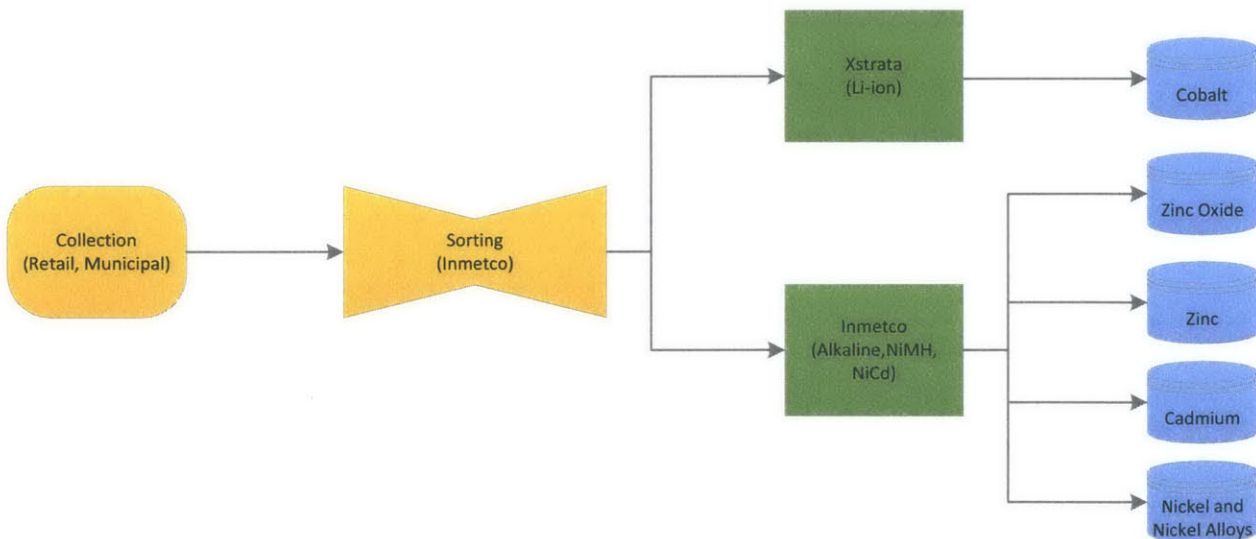


Figure 17: Call2Recycle Reverse Logistics Network - USA

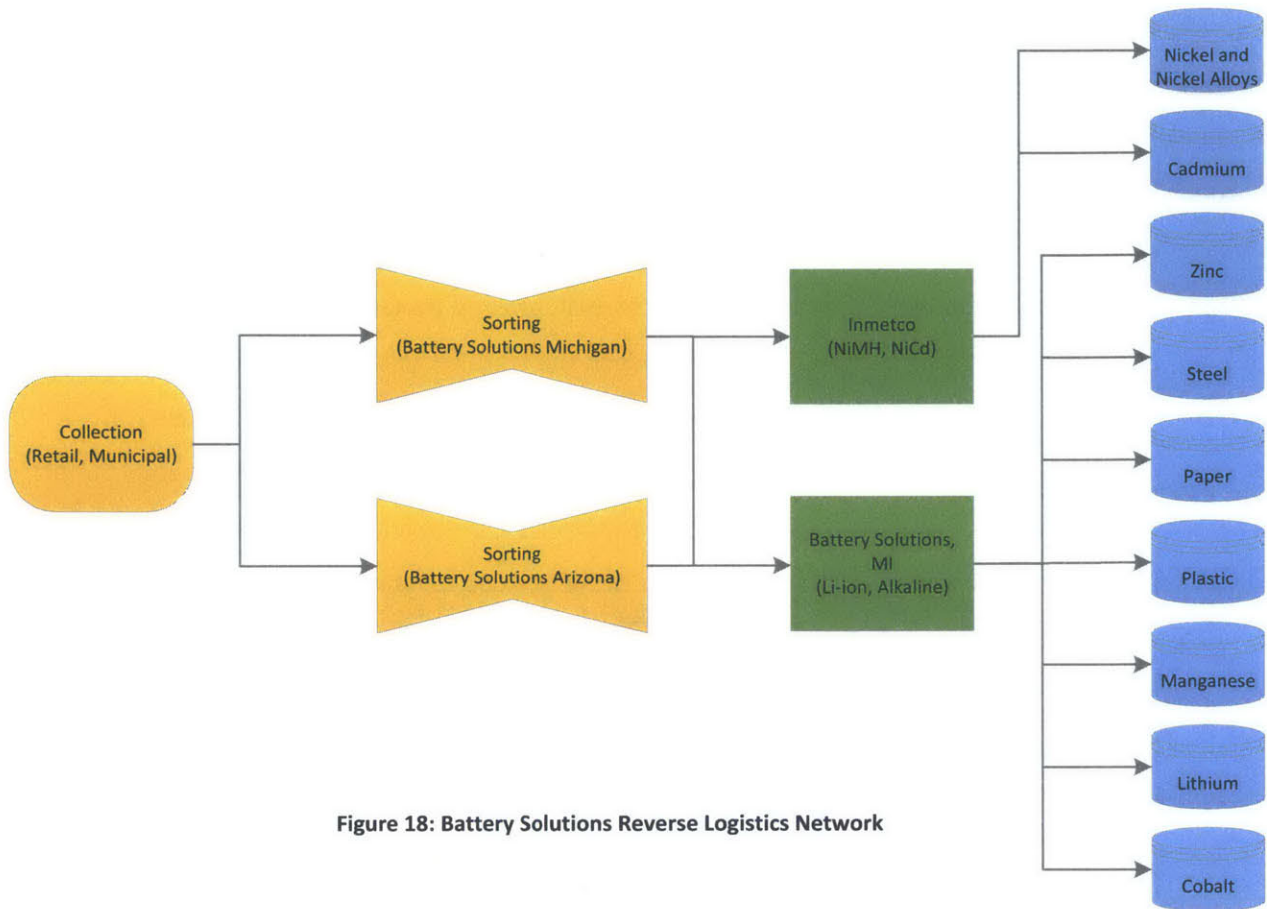


Figure 18: Battery Solutions Reverse Logistics Network



Figure 19: Map of Reverse Logistics Network Locations

Among the key differentiators of these two reverse logistics networks is presence of multiple sorting facilities in the Battery Solutions network. Section 7.2 of this paper will examine whether the presence of a second sorting facility has any positive effect from a GWP perspective. A second key difference is in the recycling of Alkaline batteries, though each of these networks recycles alkaline batteries at an integrated sorting location, the energy demands of these recycling processes are different and this will be explored in the subsequent GWP analysis. The third difference is in the recycling of Lithium-ion batteries, while these batteries are shipped from the sorting facility to the recycler in the Call2recycle/Inmetco reverse supply chain, the Battery Solutions reverse supply chain enables these batteries to be processed in a facility that is co-located with the sorting operation. While this may appear to be an important difference, as we will see in our analysis, Li-ion batteries have the least representation among collection volumes of the chemistries included in these reverse logistics networks. Thus co-locating the recycling of Li-ion batteries with the sorting activity has a negligible positive effect on the overall GWP analysis. Though the evolving regulatory landscape for li-ion batteries, which is getting increasingly restrictive in the amount of li-ion batteries that can travel together whether by air or land, makes co-location of li-ion sorting and recycling an important efficiency concern for the reverse logistics network.

Both the Call2Recycle and Battery solutions networks share retail and municipal collection methods. This means that they both are able to receive small-parcel, palletized and full truckload quantities of batteries. The exact frequency of these shipments is not known. From the sorting facility to the recycling facility material is aggregated into full truckload quantities, except in the case of li-ion batteries. The material that is recovered in the recycling process is then aggregated and can be shipped in whatever quantities are needed by the forward supply chain.

7.2 Global Warming Potential Analysis

7.2.1 Purpose

The purpose of the Global Warming Potential (GWP) analysis is to determine whether a particular reverse logistics network is more or less advantageous from a carbon footprint perspective. Section 7.1 outlines the current reverse logistics flows for consumer batteries in North America. The GWP analysis will examine both of these flows as well as potential and/or

likely hybridizations of these networks. Thus the overall goal will be to identify the most optimal reverse supply chain network from a GWP perspective.

7.2.2 Scope

There are four basic scope limitations for the GWP analysis that will be presented; system boundary, battery chemistry, geography, chosen networks. The system boundary for this reverse logistics flow GWP study will begin with the transport of collected batteries to the sorting facilities. Battery collection methods, though discussed previously, will be considered outside the scope of this analysis. The rationale for excluding battery collection methods is that all known methods (municipal drop-off, retail drop-off, and curbside collection) can be supported and are supported by both of the reverse logistics networks that are being evaluated. Thus collection method may be considered immaterial to the comparison of both reverse logistics networks. The system boundary will end with the recycling processes, thus transport to the forward supply chain will not be included in the GWP analysis. This is practical, because if included in the analysis, transport for re-introduction into the forward supply chain would appear to penalize the reverse logistics network with the most material recovered from the recycling process. In figures 20 and 21 below, the reverse logistics networks for both Call2Recycle and Battery Solutions are shown again, this time with the areas in scope for the GWP analysis highlighted.

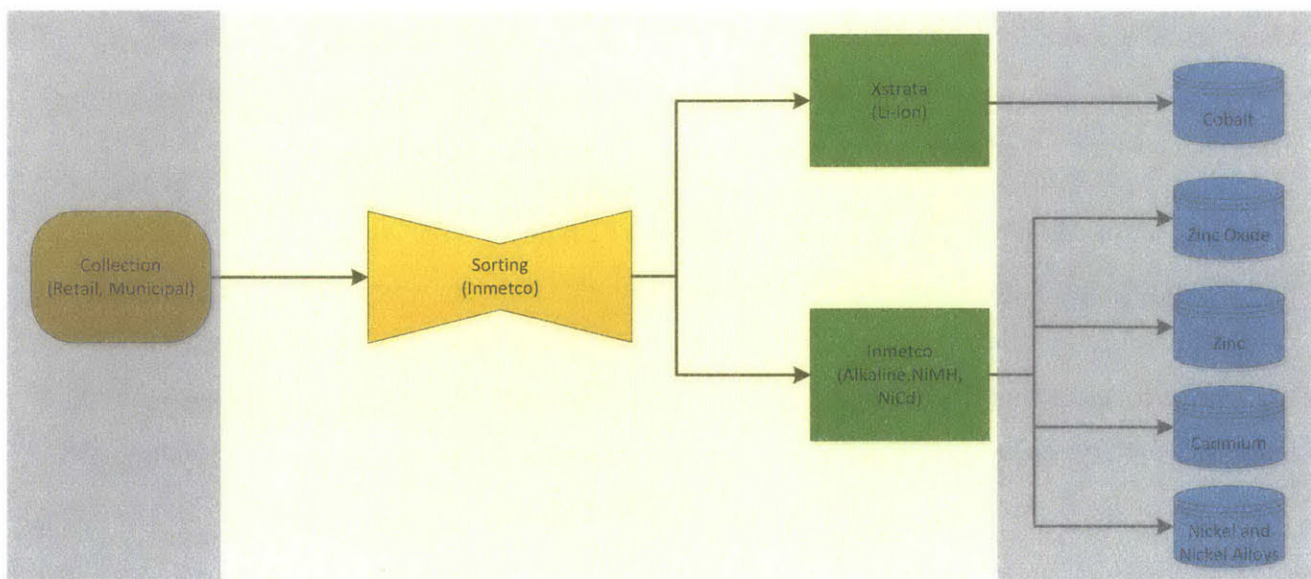


Figure 20: Functional unit boundaries for the Call2Recycle GWP Analysis

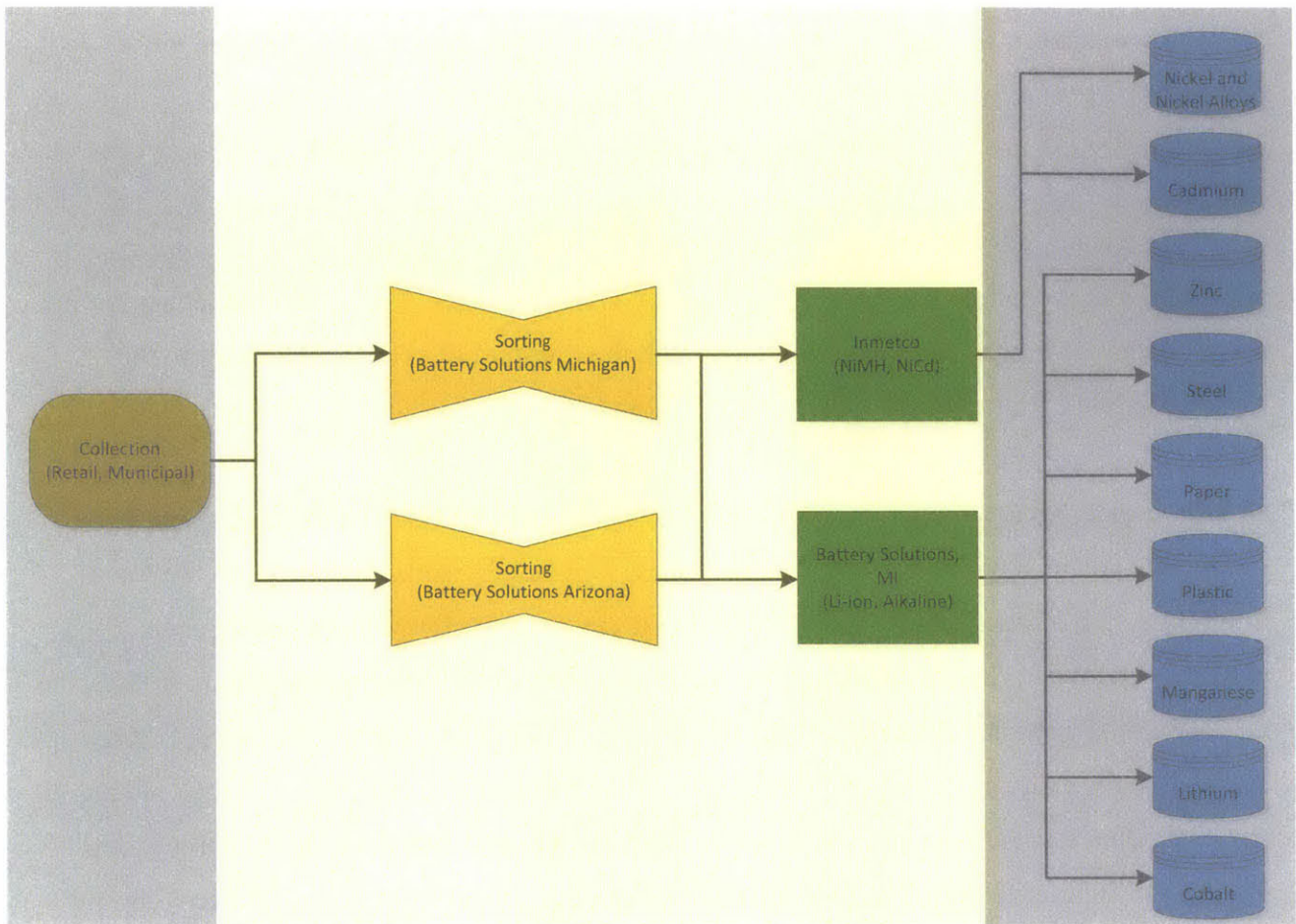


Figure 21: Functional unit boundaries for the Battery Solutions GWP Analysis

The scope of this GWP study will be limited to the following consumer battery chemistries; Alkaline, NiMH, NiCd, and Li-ion. While other chemistries are likely to be included in any systemic battery recycling effort, it will be shown that the aforementioned chemistries account for greater than 90% of all the batteries that would be recycled in North America. Thus, these chemistries will be the main drivers of the Global Warming Potential for each network and other chemistries may not have a material effect on the analysis.

In terms of Geography, the initial study will be limited to the continental United States only, though a subsequent scenario analysis will include Canadian waste battery collections. Lastly, the aforementioned reverse logistics networks for Call2Recycle and Battery Solutions will be the focus of this study. While other networks exist, these two networks appear to be the leaders in battery recycling and will likely be the two main competitors as battery recycling volumes grow.

7.2.3 Assumptions

7.2.3.1 Battery Collection Composition, by Chemistry

A number of studies have been completed that document the composition of batteries collected in North America. Since alkaline battery collection is a recent phenomenon in North America and still has almost no activity throughout the United States, many of the studies on the composition of battery collections by chemistry are not entirely relevant to the projected future state. However, a particularly useful study in understanding the impact of Alkaline batteries upon overall collection composition is the extensive study conducted by the CBR, in which they are actually managing 6 separate studies in different municipalities throughout the United States. The collection volumes for Alkaline and all other chemistries for each of these studies, as reported, has been aggregated and summarized in table 3 below. These studies will enable us to form the baseline level of alkaline battery collections that will be used in subsequent calculations.

Table 3: Collection volumes – CBR study results

Collection Area	Alkaline Proportion	Secondary Proportion	All Others
San Louis Obispo County, CA	95.9%	1.3%	2.8%
Onondaga County, NY	90.0%	10.0%	0.0%
Hennepin County, MN	85.5%	5.2%	9.3%
King County, WA	94.1%	1.3%	4.6%
Snohomish County, WA	79.3%	19.1%	1.6%
Santa Clara County, CA	79.5%	9.2%	11.3%

Overall proportion of alkaline batteries collected = 87.4%

Of the remaining batteries collected, the question that is still outstanding is: Which are Nickel based chemistries and which are Lithium based chemistries? This cannot be ascertained in the data reported by the CBR, however the Call2Recycle 2011 annual report enables us to understand the proportions of each battery chemistry collected. The data for each battery chemistry collected in 2011 is shown below, along with the overall proportion of secondary batteries collected. Using this information, we can determine the proportion of each specific battery chemistry that is likely to be collected in an a reverse logistics system that supports all consumer battery chemistries.

Overall proportion of Secondary batteries collected = 7.7%

Table 4: Secondary battery collection metrics

Chemistry	Collection Volume (lbs)	Proportion of Secondary Chemistry Stream	Proportion of Overall Collections
Nickel Cadmium	2,800,000	51.4%	4.0%
Nickel Metal Hydride	950,000	17.4%	1.3%
Lithium Ion	1,700,000	31.2%	2.4%

It is important to note that based on the studies conducted and summarized above, there is some proportion of batteries (approximately 4.9%), that remains unaccounted for. These are generally other types of primary batteries (button, lithium primary) and lead-acid secondary batteries. For the purpose this analysis, these battery types will be considered out of scope.

The functional Unit of Measure for the GWP study will be one metric ton of household consumer batteries collected for recycling. The nature of flows within the network allows for the aggregation of material to avoid less than full truckloads. Thus the proportions above must be related to metric tons in order to appropriately execute the study. There are four basic material input flows in the study; all batteries collected, Alkaline batteries, Nickel bearing batteries, and Lithium-ion batteries. Using the percentages above, the smallest of the aforementioned material flows is that for Lithium-ion, thus the other material flows will be related to this material flow to determine the magnitude and amount of each material flow. Table 5 is a summary of these proportional flows in which the numbers have been rounded to adhere to the functional unit constraint.

Table 5: Battery chemistry functional units

Battery Chemistry	Metric Tons
Alkaline	36
Nickel Bearing	2
Lithium Ion	1

Note that based on the table above, the total amount of batteries processed in the analysis will be 39 metric tons.

7.2.3.2 Determining Anticipated Collection Volumes

Detailed information regarding the unit volume of annual sales and the average weight per unit of each battery chemistry studied could not be found. However, information does exist for the U.S. based alkaline battery sales unit volumes and weight per unit. As shown in section 7.2.3.1, these batteries account for greater than 87% of the forecasted battery collections, so this data may represent a workable approximation of the total battery market. The unit volume of alkaline sales in 2010 was approximately 4.1 billion batteries³⁸. Utilizing the weighted average alkaline battery metric of 33g³⁹, the annual tonnage of alkaline batteries sold in 2010 is approximated to be 135,432 tons of Alkaline batteries.

Since this paper focuses on the potential of a consumer battery reverse logistics network, perhaps the best benchmark in which to understand potential collection volumes would be the EU 2006 battery directive take-back targets. These minimum battery collection targets are shown below.

- 25% by September 26, 2012
- 45% by September 26, 2016⁴⁰

Given the uncertainty of what may be achieved in North America, anticipated collection volumes will be estimated using sensitivity analysis. This analysis will include the entire range of the EU battery directive take-back targets, using the 2016 target as an upper boundary. Since data to approximate the weight of rechargeable batteries sold could not be found, the weight of rechargeable batteries collected will be assumed to be proportional to Alkaline collection rates as observed and characterized in section 7.2.3.1. Figure 22 below shows the results of the collection volume sensitivity analysis.

³⁸ (Corporation for Battery Recycling, 2011)

³⁹ (Olivetti, Gregory, & Kirchain, 2011)

⁴⁰ (European Parliament and the Council of the European Union, 2006)

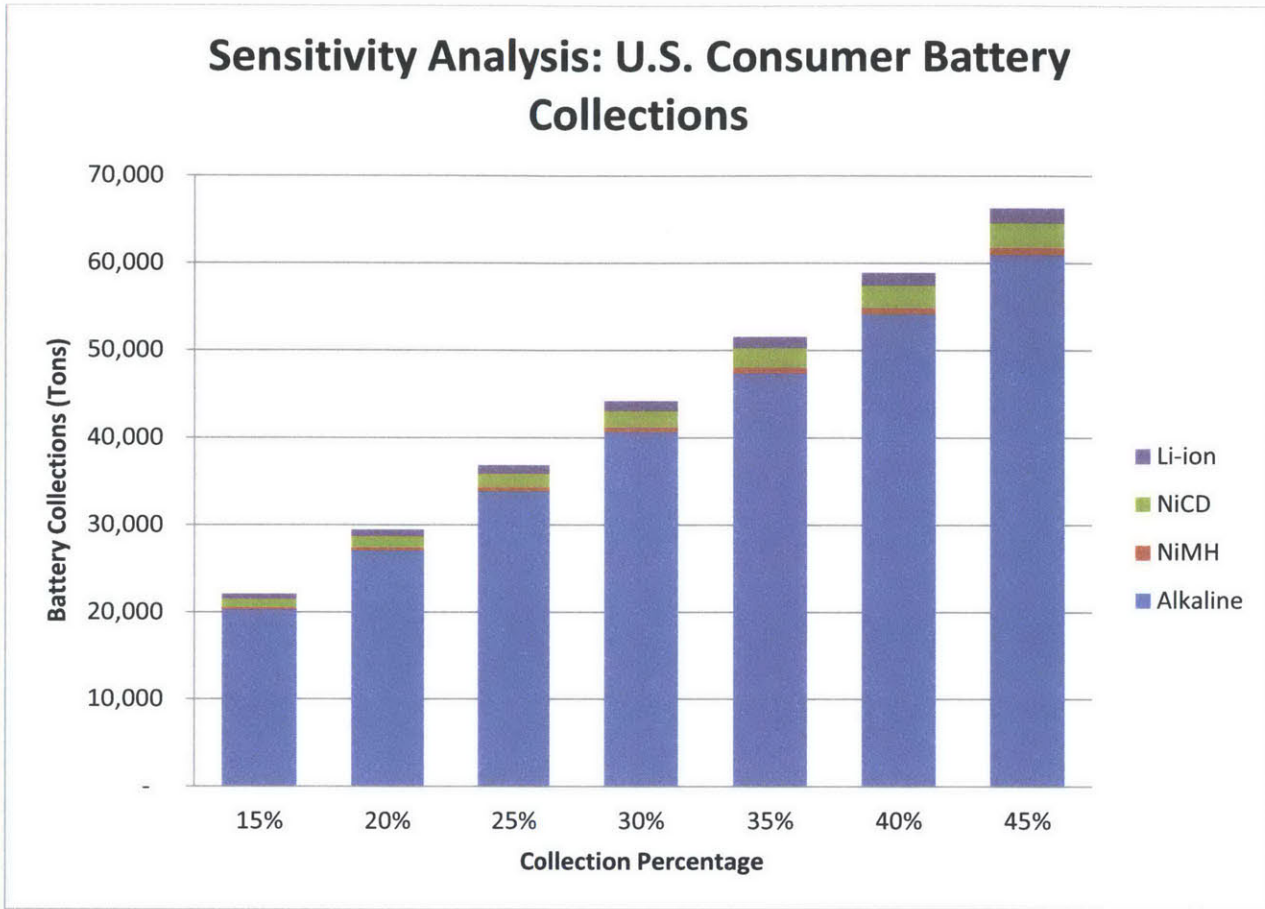


Figure 22: Sensitivity Analysis of U.S. Consumer Battery

7.2.3.3 Energy Usage Assumptions

To determine energy usage assumptions for the processes in the reverse logistics networks modeled, research was carried out within the existing Life Cycle Analyses conducted in the battery space. While detail level data may not exist for the exact processes studied, high level data exists for each process category. For example, though the specific energy consumption data for the NiMH recycling process at Inmetco is unknown, the aforementioned 2006 LCA lists energy consumption data for a pyrometallurgical recycling process for this battery chemistry. In this way, suitable and rational energy usage metrics were found for each step examined in the reverse logistics network. Human energy (labor) was not considered, only electricity, gas and fuel consumption as well as transportation were considered.

To execute the GWP study and thus determine CO2 emissions, emission factors are needed to convert electricity consumption into CO2 emissions. The United States Department of

Energy (DOE) maintains a reference for electricity emission factors that are localized by region within the US, and by nation for foreign electrical consumption. The emissions factors utilized in this analysis are taken from this source⁴¹. Greenhouse gas emissions from transportation flows are also determined using emissions factors. These are taken from a variety of sources including The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) provided by Argonne National Laboratory, IPCC, and the International Energy Agency. A summary of the energy consumption and emissions factors utilized in this analysis is provided in the table below:

Table 6: Emissions Factors

Process	Battery Units of Measure	Activity Data	Activity Units of Measure	Units of Measure	Emission Factor (kg CO₂e)
Land Transport by truck	Ton	See section 7.2.3.4	miles	ton-mile	0.086 ⁴²
Sorting (Battery Solutions Arizona)	Ton	2.4	kWh/ton	kWh	0.658
Sorting (Battery Solutions Michigan and Inmetco)	Ton	2.4	kWh/ton	kWh	0.782
Battery Solutions (Alkaline Recycling - Hydrometallurgical)	Ton	959	kWh/ton	kWh	0.782
Inmetco (Alkaline Recycling - Pyrometallurgical)	Ton	1690	kWh/ton	kWh	0.782
	Ton	58	Kg Fuel oil/ton	kg	3.127
Inmetco (NiMH/NiCd Recycling - Pyrometallurgical)	Ton	1242	kWh/ton	kWh	0.782
	Ton	152	Kg Nat gas/ton	kg	2.692
Battery Solutions (Li-ion Recycling - Hydrometallurgical)	Ton	140	kWh/ton	kWh	0.782
Xstrata (Li-ion Recycling - Pyrometallurgical)	Ton	800	kWh/ton	kWh	0.223

⁴¹ (United States Department of Energy, 2007)

⁴² (Blanco, SC Carbon Footprint Case Study Data, 2008)

7.2.3.4 Land Transport distances

To simulate land transport from throughout the United States, a composite land transport index “I” was developed. The calculation for this index is weighted average transport measure with the exact parameters as shown in the formula below:

$$I = \left\{ \sum_i (b_i \times p_i \times m_{ij}) \right\} / 20$$

where,

I = weighted average distance for battery transport from collection points to sorting facility

i = metropolitan area, the 20 largest U.S. metropolitan areas are used for this metric

b = batteries collected per capita

p = population of the metropolitan area

m = distance of the metropolitan area in miles from the sorting facility j

j = sorting facility

In an absence of actual data regarding the volumes of battery reverse logistics material flows as they relate to the specific metropolitan areas, due primarily to the lack of municipally organized battery collections in these areas, “b” in the equation above can be argued to be a constant. Thus, the composite index was derived from a weighted average distance from the sorting aggregation point to the 20 largest metropolitan areas in the United States (as determined by the US Census Bureau in the 2010 census). Given that “b” has been declared to be a constant, the weighted average used represents the percent of population represented by the metropolitan area in comparison to the total population of all 20 areas. The logic for this is that the larger metropolitan areas would send more batteries to the sorting facility than the smaller metropolitan areas and thus should have a higher representation in the weighted average index of transport

distance. To illustrate the concept, the table used to calculate this index for the Call2Recycle network is shown below.

Table 7: Derivation of the land transport weighted average

Metropolitan statistical area	2010 Census	% weight	Distance from Ellwood City, PA	Distance Contributed to Composite Index
New York-Northern New Jersey-Long Island, NY-NJ-PA	18,897,109	16%	394	64
Los Angeles-Long Beach-Santa Ana, CA	12,828,837	11%	2430	270
Chicago-Joliet-Naperville, IL-IN-WI	9,461,105	8%	431	35
Dallas-Fort Worth-Arlington, TX	6,371,773	6%	1243	69
Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	5,965,343	5%	339	17
Houston-Sugar Land-Baytown, TX	5,946,800	5%	1358	70
Washington-Arlington-Alexandria, DC-VA-MD-WV	5,582,170	5%	279	13
Miami-Fort Lauderdale-Pompano Beach, FL	5,564,635	5%	1208	58
Atlanta-Sandy Springs-Marietta, GA	5,268,860	5%	718	33
Boston-Cambridge-Quincy, MA-NH	4,552,402	4%	595	23
San Francisco-Oakland-Fremont, CA	4,335,391	4%	2546	95
Detroit-Warren-Livonia, MI	4,296,250	4%	255	9
Riverside-San Bernardino-Ontario, CA	4,224,851	4%	2398	88
Phoenix-Mesa-Glendale, AZ	4,192,887	4%	2064	75
Seattle-Tacoma-Bellevue, WA	3,439,809	3%	2493	74
Minneapolis-St. Paul-Bloomington, MN-WI	3,279,833	3%	838	24
San Diego-Carlsbad-San Marcos, CA	3,095,313	3%	2468	66
St. Louis, MO-IL	2,812,896	2%	620	15
Tampa-St. Petersburg-Clearwater, FL	2,783,243	2%	1059	25
Baltimore-Towson, MD	2,710,489	2%	281	7

Weighted Average Distance = 1,132 miles

The distances used were found through Google maps and represent the generic distance from the anchor city in the major metropolitan area to the generic location of Ellwood City, PA. Specific addresses were not utilized as they would not materially impact the analysis.

This composite index represents over 115 million Americans, which is approximately 37% of the total U.S. population. This selected 20 major metropolitan areas touches all of the major states with pending legislation and or significant and disproportionate consumer battery recycling collections, these include New York, Minnesota, Washington, and California. The only state with significant legislative activity that has been excluded from this index is Rhode

Island. However, the greater Boston metropolitan area represents a significant flow of batteries from the NorthEast region of the United States and may represent an approximation of the distance and flow of batteries from Rhode Island.

A similar analysis was carried out on the Battery Solutions reverse logistics network to determine the composite index for distance to the sorting location. However, in the case of Battery Solutions, the reverse logistics network contains two sorting facilities; one in Mesa, Arizona and another in Howell, Michigan. For this analysis, the same 20 cities were used as the basis of the composite index calculation. The difference in this analysis was that the distances to the sorting facility were calculated for both the Mesa, Arizona and Howell, Michigan locations and the metropolitan areas were grouped in accordance with the lesser of the two distances. Composite indexes were then calculated for both groups to determine weighted average trip miles to both recycling facilities. A notable decrease in weighted average trip miles was observed with these being 724 miles for transport to the Howell, Michigan sorting facility and 668 miles for transport to Mesa, Arizona. Lastly, given the mix of metropolitan areas under consideration, the material flows between both sorting facilities will not be evenly split. Again, population was used as the relative indicator of material flow volumes and it was determined that 61.5% of the batteries collected would flow to Howell Michigan, while the remaining 38.5% would flow to Mesa, Arizona. The tables used for calculation of these metrics are shown in the appendix.

7.2.4 Results

7.2.4.1 Carbon Footprint

The overall results of the carbon footprint analysis of the primary reverse logistics systems for consumer battery recycling show the Battery Solutions network to have far less environmental impact than the Call2Recycle network. The overall results are as follows:

- Call2Recycle = 1,563 Kg CO₂ equivalents per metric ton of batteries collected
- Battery Solutions = 782 Kg CO₂ equivalents per metric ton of batteries collected

Perhaps on the surface, this may appear to be due to the existence of a second regionally located sorting facility in the Battery Solutions network, however a careful review of the data tells a

different story. The summarized data for both the Battery Solutions and Call2Recycle networks are as follows.

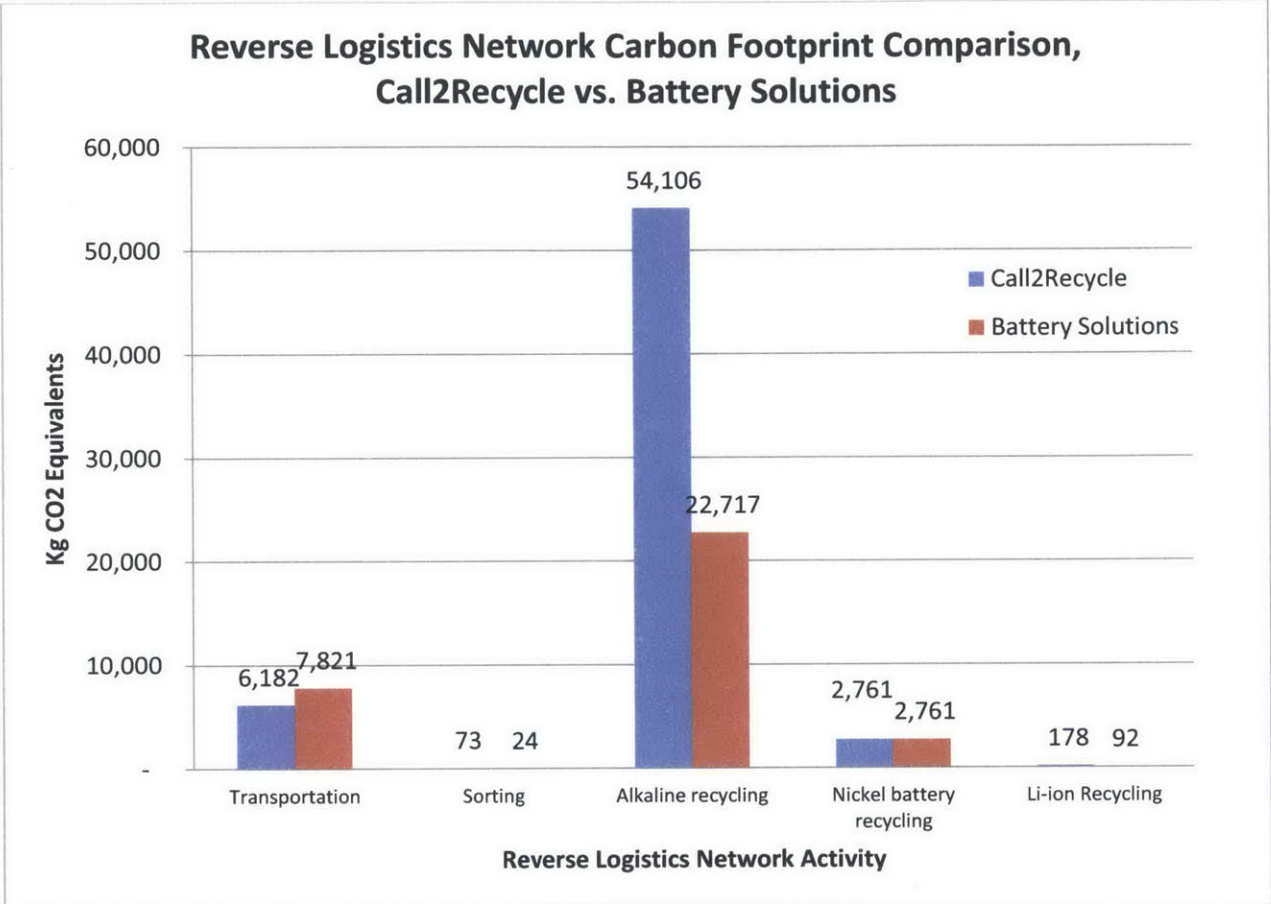


Figure 23: Carbon Footprint Comparison

Reverse Logistics Network Carbon Footprint Analysis: Call2Recycle vs. Battery Solutions

Table 8: Carbon Footprint Data

Activity	Process	Amount (kg)	Activity Data	Units of Measure	Computed Data	Units of Measure	Emission Factor (kg CO2e)	Total CO2-Eq (Kg)	% of Overall Emissions
Transport to Sorting Location	Land Transport	39000	1132	miles	44148.0	ton-mile	0.1384	6110	9.7%
Sorting @ Inmetco	Manual Sorting	39000	2.4	kWh/ton	93.6	kWh	0.782	73	0.1%
Alkaline recycling	Pyrometallurgical	36000	1690	kWh/ton	60840.0	kWh	0.782	47577	75.2%
	Pyrometallurgical	36000	58	kg Fuel oil/ton	2088.0	kg	3.127	6529	10.3%
Nickel battery recycling	Pyrometallurgical	2000	1242	kWh/ton	2484.0	kWh	0.782	1942	3.1%
	Pyrometallurgical	2000	152	kg Nat gas/ton	304.0	kg	2.692	818	1.3%
Transport to Li-ion recycler	Land Transport	1000	521	miles	521.0	ton-mile	0.1384	72	0.1%
Li-ion Recycling	Pyrometallurgical	1000	800	kWh/ton	800.0	kWh	0.223	178	0.3%
Total								63301	

Battery Solutions

Activity	Process	Amount (kg)	Activity Data	Units of Measure	Computed Data	Units of Measure	Emission Factor (kg CO2e)	Total CO2-Eq (Kg)	% of Overall Emissions
Transport to Sorting Location - Mesa, AZ	Land Transport	15015	668	miles	10030.0	ton-mile	0.1384	1388	4.1%
Transport to Sorting Location - Howell, MI	Land Transport	23985	724	miles	17365.1	ton-mile	0.1384	2403	7.2%
Sorting @ Battery solutions Mesa, AZ	Manual Sorting	15015	2.4	kWh/ton	36.0	kWh	0.658	24	0.1%
Sorting @ Battery solutions Howell, MI	Manual Sorting	23985	2.4	kWh/ton	57.6	kWh	0.782	45	0.1%
Transport to Alkaline/Li-ion Recycling from Mesa	Land Transport	13860	1961	miles	27179.5	ton-mile	0.1384	3762	11.2%
Transport to nickel battery recycling from Mesa	Land Transport	770	2062	miles	1587.7	ton-mile	0.1384	220	0.7%
Transport to nickel battery recycling from Howell	Land Transport	1230	285	miles	350.6	ton-mile	0.1384	49	0.1%
Alkaline recycling	Hydrometallurgical	36000	959	kWh/ton	34524.0	kWh	0.658	22717	67.9%
	Pyrometallurgical	2000	1242	kWh/ton	2484.0	kWh	0.782	1942	5.8%
Nickel battery recycling	Pyrometallurgical	2000	152	kg Nat gas/ton	304.0	kg	2.692	818	2.4%
	Hydrometallurgical	1000	140	kWh/ton	140.0	kWh	0.658	92	0.3%
Total								33460	

From a logistics and transportation perspective, the Battery Solutions reverse logistics network actually has a higher carbon footprint than the Call2Recycle network. This is despite the presence of a second region aggregation point for battery collections in the Battery Solutions network. However, it should be noted that the carbon footprint due to inbound transport for the Battery Solutions network is lower than that of Call2Recycle, and thus the increase in overall transportation carbon footprint is due to outbound transportation from the transport from the sorting facility to the recycling location. In this way, we can visualize the potential positive impact from additional recycling facilities that may be co-located with sorting facilities.

The difference then must be explained in the other facets of the reverse logistics network. In this case, the primary difference is the presence of pyrometallurgical recycling in the Call2Recycle reverse logistics network. The environmental impact, in terms of carbon footprint, is much higher than hydrometallurgical processes. In fact, if we look at only the recycling burden of each network, we can see the magnitude of these differences. The Call2Recycle network has over 2 times the carbon footprint from recycling activities as compared to the Battery Solutions alternative. The data is shown below.

- Call2Recycle = 1,463 Kg CO₂ equivalents per metric ton of batteries recycled
- Battery Solutions = 656 Kg CO₂ equivalents per metric ton of batteries recycled

Given that the primary difference in these two reverse logistics networks is in the recycling methods used, and the proportion of the carbon footprint that is derived from recycling activities, we may conclude that the transportation differences of these reverse logistic networks are negligible.

7.2.4.2 Global Warming Potential

To determine overall global warming potential, we must include the impact of Methane and Nitrous Oxide gases. These gases are emitted in far smaller quantities than Carbon Dioxide but have a larger impact on global warming potential on a per unit basis. This is because both Methane and Nitrous Oxide trap more heat in the atmosphere than Carbon Dioxide on a per unit basis. To determine the magnitude of the GWP of each gas, we must identify a time horizon for the GWP study, this is due to the degradation of the gas in the atmosphere over time. The following study utilized a 20 year GWP time horizon. When we balance the disproportionate

emissions of Carbon Dioxide with the 20 year GWP impact of Methane and Nitrous Oxide, we find the overall impact of the latter 2 gases to have an almost negligible impact from an environmental perspective. In comparison to the carbon footprint studies, the percent increase in overall kg CO2 equivalents for the GWP study for both networks is shown below.

- Call2Recycle = 0.82% increase in kg CO2 equivalents
- Battery Solutions = 0.66% increase in kg CO2 equivalents

It is important to note that the Methane and Nitrous Oxide emissions are direct factors of the activities in the reverse logistics network. Thus, since the reverse logistics networks are unchanged, the drivers of the GWP analysis are the same as the carbon footprint analysis. This means that, though the proportions may differ slightly, the same conclusions may be reached by both the carbon footprint and GWP studies. The GWP is driven by the recycling methods utilized and thus the ideal network from an environmental impact perspective, as measured by GWP, is the Battery Solutions network. The results of the GWP study are shown on the following pages.

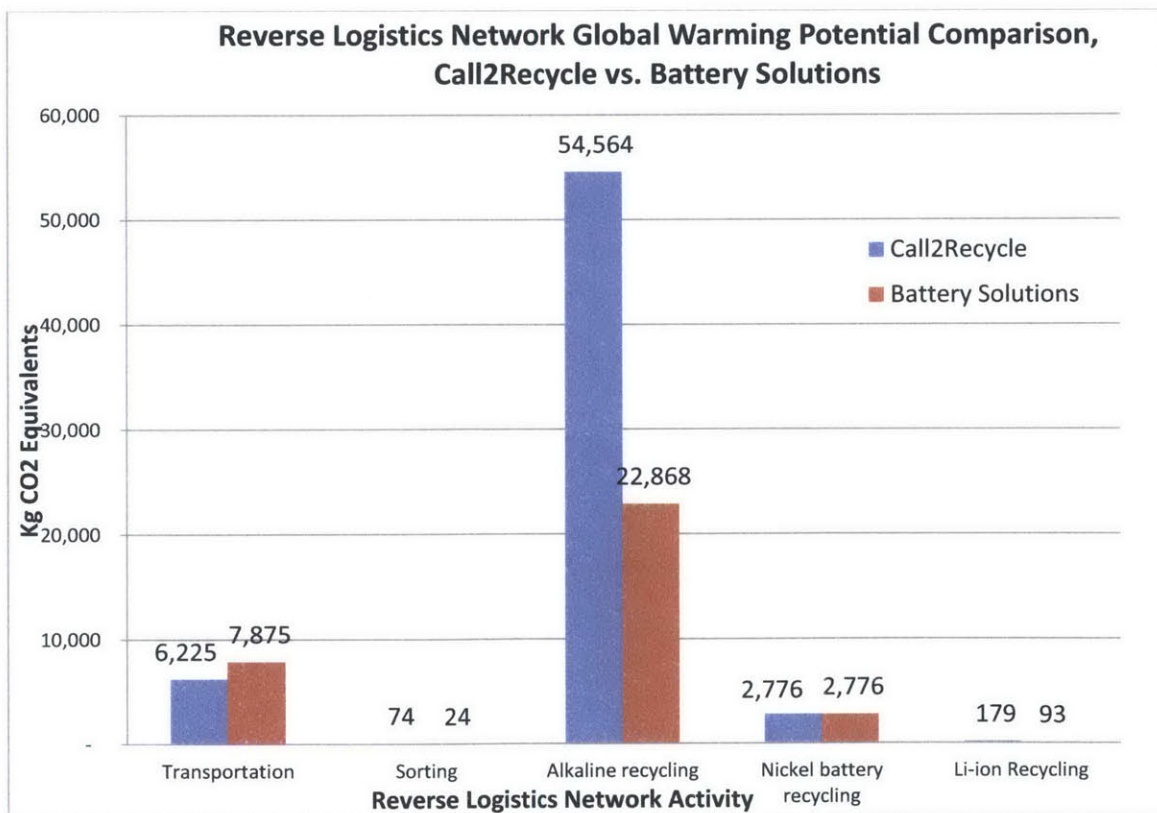


Figure 24: Global Warming Potential Comparison

Reverse Logistics Network Global Warming Potential Analysis: Call2Recycle vs. Battery Solutions

Table 9: Global Warming Potential Data

Activity	Process	Amount (kg)	Activity Data	Units of Measure	Computed Data	Units of Measure	Emission Factor (kg CO2e)	Emission Factor (g CH4e)	20 year GWP (kg CO2e)	Emission Factor (g N2Oe)	20 year GWP (kg CO2e)	Total GWP (kg CO2e)	% of Overall Emissions
Transport to Sorting Location - Sorting @ Inmetco	Land Transport	39000	1132	miles	44148	ton-mile	0.1384	0.0035	56	0.0027	280	6152	9.6%
Alkaline recycling	Manual Sorting	39000	2.4	kWh/ton	93.6	kWh	0.782	0.01404	56	0.01281	280	74	0.1%
Nickel battery recycling	Pyrometallurgical	36000	1690	kWh/ton	60840	kWh	0.782	0.01404	56	0.01281	280	47843	75.0%
Transport to Li-ion recycler	Pyrometallurgical	36000	58	kg Fuel oil/ton	2088	kg	3.127	0.43	56	0.2424	280	6721	10.5%
Li-ion Recycling	Pyrometallurgical	2000	1242	kWh/ton	2484	kWh	0.782	0.01404	56	0.01281	280	1953	3.1%
	Pyrometallurgical	2000	152	kg Nat gas/ton	304	kg	2.692	0.24	56	0.0048	280	823	1.3%
	Land Transport	1000	521	miles	521	ton-mile	0.1384	0.0035	56	0.0027	280	73	0.1%
	Pyrometallurgical	1000	800	kWh/ton	800	kWh	0.223	0.0039	56	0.00351	280	179	0.3%
Total												63818	

Battery Solutions

Activity	Process	Amount (kg)	Activity Data	Units of Measure	Computed Data	Units of Measure	Emission Factor (kg CO2e)	Emission Factor (g CH4e)	20 year GWP (kg CO2e)	Emission Factor (g N2Oe)	20 year GWP (kg CO2e)	Total GWP (kg CO2e)	% of Overall Emissions
Transport to Sorting Location - Mesa, AZ	Land Transport	15015	668	miles	10030.02	ton-mile	0.1384	0.0035	56	0.0027	280	1398	4.1%
Alkaline recycling	Land Transport	23985	724	miles	17365.14	ton-mile	0.1384	0.0035	56	0.0027	280	2420	7.2%
Nickel battery recycling	Manual Sorting	15015	2.4	kWh/ton	36.036	kWh	0.658	0.00762	56	0.00941	280	24	0.1%
Li-ion Recycling	Manual Sorting	23985	2.4	kWh/ton	57.564	kWh	0.782	0.01404	56	0.01281	280	45	0.1%
Transport to nickel battery recycling from Mesa	Land Transport	13860	1961	miles	27179.46	ton-mile	0.1384	0.0035	56	0.0027	280	3788	11.2%
Transport to nickel battery recycling from Mesa	Land Transport	770	2062	miles	1587.74	ton-mile	0.1384	0.0035	56	0.0027	280	221	0.7%
Alkaline recycling	Land Transport	1230	285	miles	350.55	ton-mile	0.1384	0.0035	56	0.0027	280	49	0.1%
Nickel battery recycling	Hydrometallurgical	36000	959	kWh/ton	34524	kWh	0.658	0.01404	56	0.01281	280	22858	67.9%
Li-ion Recycling	Pyrometallurgical	2000	1242	kWh/ton	2484	kWh	0.782	0.01404	56	0.01281	280	1953	5.8%
	Pyrometallurgical	2000	152	kg Nat gas/ton	304	kg	2.692	0.24	56	0.0048	280	823	2.4%
	Hydrometallurgical	1000	140	kWh/ton	140	kWh	0.658	0.01404	56	0.01281	280	93	0.3%
Total												33681	

7.2.5 Implications for Overall N. American Collection Volumes

While the carbon footprint and GWP analyses have shown the Battery Solutions network to be more environmentally advantageous, the analyses were run only on a basis of 39 metric tons of recovered batteries. To better understand the practical magnitude of this difference, we must compare this observed difference to the potential volume of collections for consumer batteries as defined in section 7.2.3.2. Since anticipated collection volumes have been defined, a linear projection can be used to estimate the carbon footprint and GWP. Figure 27 illustrates the linear projections for GWP for both reverse logistics networks.

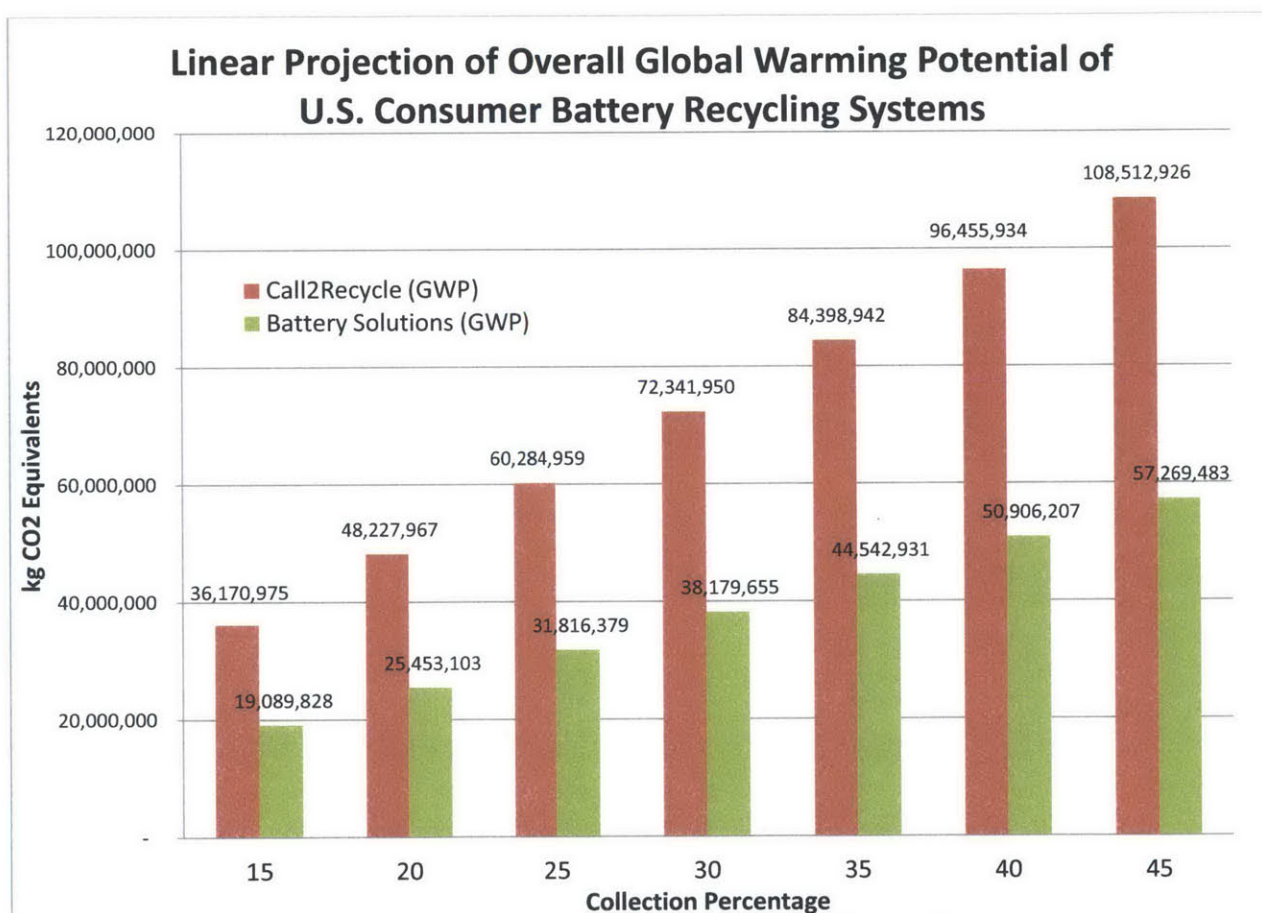


Figure 25: Linear Projection of Overall Global Warming Potential

It can be seen from the sensitivity analysis that the range of difference in terms of GWP of the two networks may be as great as 51,243,443 kg CO2 equivalents in any given year. While this may seem like a large number, to better understand this, we must place it in perspective. The average annual GWP per U.S. resident is approximately 20,000 kg CO2 equivalents.

Utilizing this number, we can determine that this difference is only equal to the GWP for 2,562 U.S. residents. Thus we may be able to consider this difference inconsequential.

7.2.8 Additional Considerations

7.2.8.1 Materials Recovered

The previous analyses have focused solely on environmental impact through the direct greenhouse gas generation of the reverse logistics network activities. However, another critical factor to consider when evaluating reverse logistics networks, and specifically their corresponding recycling systems, is the amount and type of materials recovered. As we compare and contrast the Call2Recycle network and the Battery Solutions network, we will see that the Battery Solutions network offers a premium in terms of materials recovered. This is primarily due to the use of lower temperature recycling processes in the Battery Solutions network which enable the recovery of nearly all battery component materials.

Since Alkaline batteries account for greater than 85% of the consumer waste stream, let's first compare and contrast the recycling process for this battery chemistry in terms of recovered materials. The Call2Recycle network processes alkaline material at Inmetco in a high temperature pyrometallurgical process in which many of the battery materials are consumed and recovery is limited to Zinc and Zinc Oxide metals⁴³. Though it is unclear what proportion of the Zinc material introduced to the recycling process is recovered, we know that this material represents only 18% of the overall weight of the battery. In comparison, the Battery Solutions process claims to recover nearly 100% of the battery components and has identified re-entry points for all materials except the paper and plastic mixture⁴⁴. A site visit to this recycling process validated this claim, with the only notable exception being the absence of Potassium Hydroxide (KOH) recovery. KOH accounts for 11% of the overall battery weight. Excluding KOH and the paper and plastic mixture, the Battery Solutions process is still able to recover 86% of the Alkaline battery materials. Figure 28 provided by Battery Solutions highlights the outflows from the Alkaline recycling process.

⁴³ (Smith, 2013)

⁴⁴ (Sova, 2013)

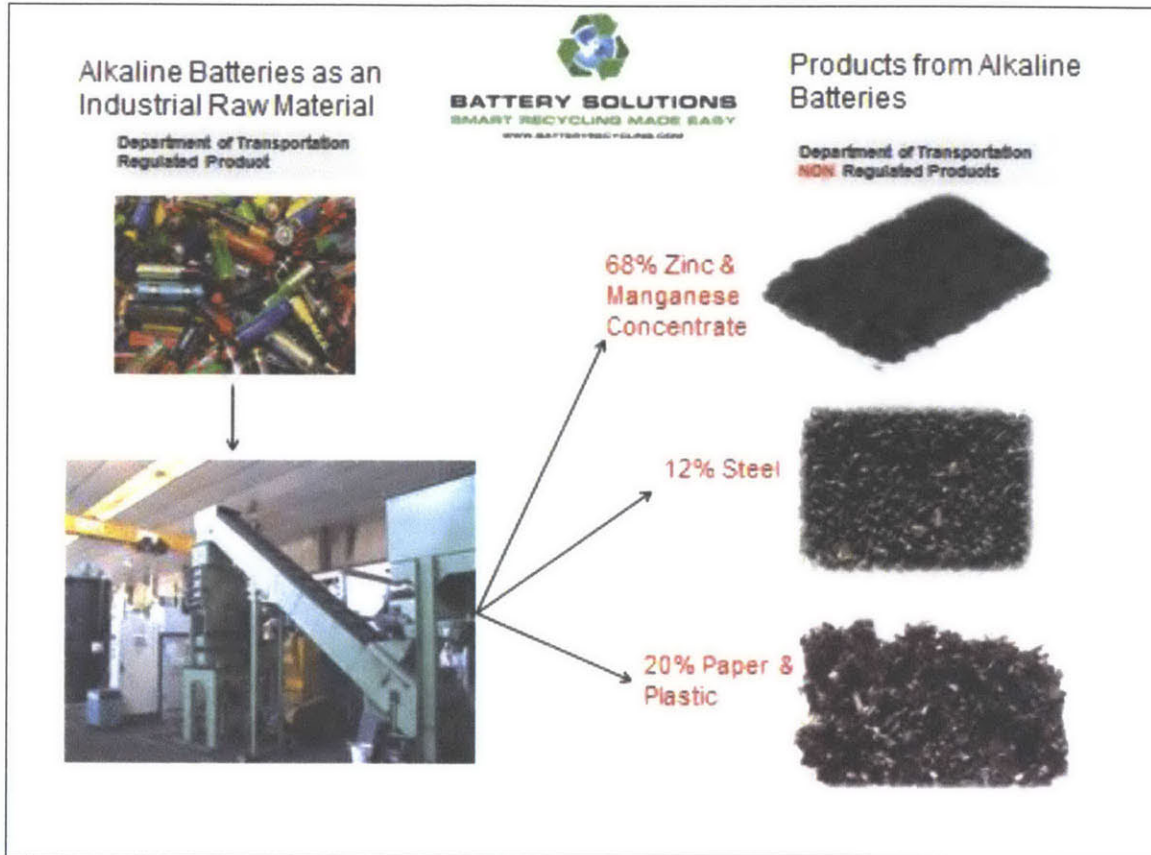


Figure 26: Alkaline Battery Recycling (Sova, 2013)

For Nickel based batteries, both Call2Recycle and Battery Solutions are utilizing Inmetco to process these materials, thus no material recovery advantage exists in either reverse logistics network. However, the networks differ again in the recycling methods of Li-ion batteries, with this difference also being due to high temperature vs. low temperature processing. Though specific information regarding the recycling process at Xstrata (the Li-ion recycler for Call2Recycle) could not be found, the process is known to be pyrometallurgical. Material recovery data for pyrometallurgical Li-ion battery recycling can be found in the 2006 Battery waste management LCA. In this case the following materials are recovered; Cobalt powder, Manganese Dioxide, Steel, non-ferrous metals. In contrast to Alkaline recycling, the pyrometallurgical recycling process for Li-ion batteries is much closer to the hydrometallurgical process used by Battery Solutions from a materials recovery perspective. The most notable differences in material recovery are that the Battery Solutions process is able to recover Lithium salts, but does not recover discrete Manganese Dioxide. Table 10 details the materials recovered by each reverse logistics network,

**Table 10: Materials Recovered Through Consumer Battery Recycling
Reverse Logistics Network**

Battery Chemistry	Call2Recycle	Battery Solutions
Li-ion	Cobalt Powder	Lithium Salt
	Manganese Dioxide	Cobalt Salt
	Steel	Steel
	non-ferrous metals	non-ferrous metals
Nickel-based	Cadmium	
	Nickel	
	Iron	
Alkaline	Zinc	Zinc
	Zinc Oxide	Manganese
		Paper
		Plastic
		Steel

7.2.8.1 Cost

In any product recycling scenario, cost plays a key role in the viability of the reverse logistics network. Though it is difficult to assess a direct cost to each of the networks examined, literature is available on the comparison between recycling and landfilling consumer batteries. This data shows that the cost of recycling consumer batteries is much higher than the cost to landfill these batteries by an approximate factor of 50 to 1, with a cost of \$1.02 per of batteries recycled versus \$0.02 per pound of batteries landfilled⁴⁵. Given this cost burden, incentives must exist along the reverse supply chain that enable profitable operation for the firms who wish to participate in the network. Extended Producer Responsibility is one way in which this cost will be assessed and this obstacle to product recycling surmounted. Perhaps Carl Smith, CEO Call2Recycle has the correct outlook when it comes to developing a reverse logistics network for the collection and recycling of batteries. Mr. Smith contends that the sole objective for the Call2Recycle network is collections – not cost, and that optimizations can be made in the future when a sufficient collections volume and infrastructure are in place. Mr. Smith compares this

⁴⁵ (Corporation for Battery Recycling, 2011)

strategy to a for profit start-up that would first work to build revenues and then later focus upon profitability⁴⁶.

To optimize the overall cost of the reverse logistics network, the key cost drivers of each activity in the reverse supply chain must be understood. With this understanding, regulators and key stakeholders may be able to devise systems of lowest total cost and maximum realizable economies of scale. Figure 29 below summarizes the key cost and revenue drivers of the reverse logistics network⁴⁷.

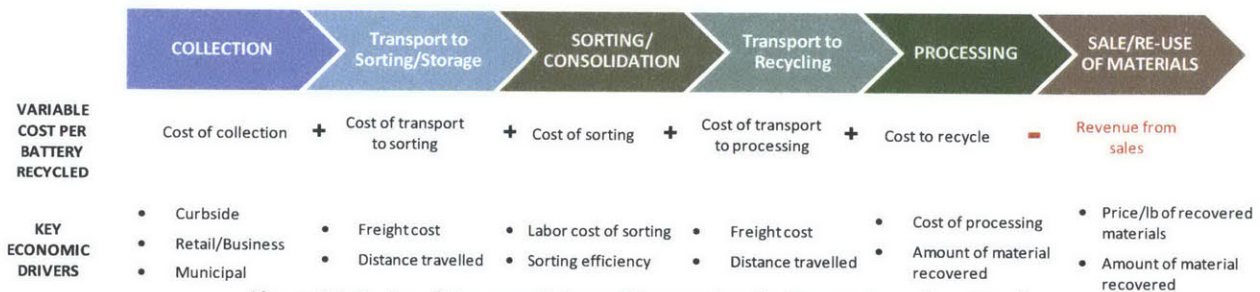


Figure 27: Cost and Revenue Drivers (Corporation for Battery Recycling, 2011)

To better understand the magnitude of these costs in the scope of the overall reverse logistics network, figure 30 is presented below⁴⁸. This chart presents data for three scenarios: collection and recycling of spent batteries; separate collection and landfill of these batteries; and finally collection and landfill within the existing municipal waste stream with no special handling.

⁴⁶ (Smith, 2013)

⁴⁷ (Corporation for Battery Recycling, 2011)

⁴⁸ (Corporation for Battery Recycling, 2011)

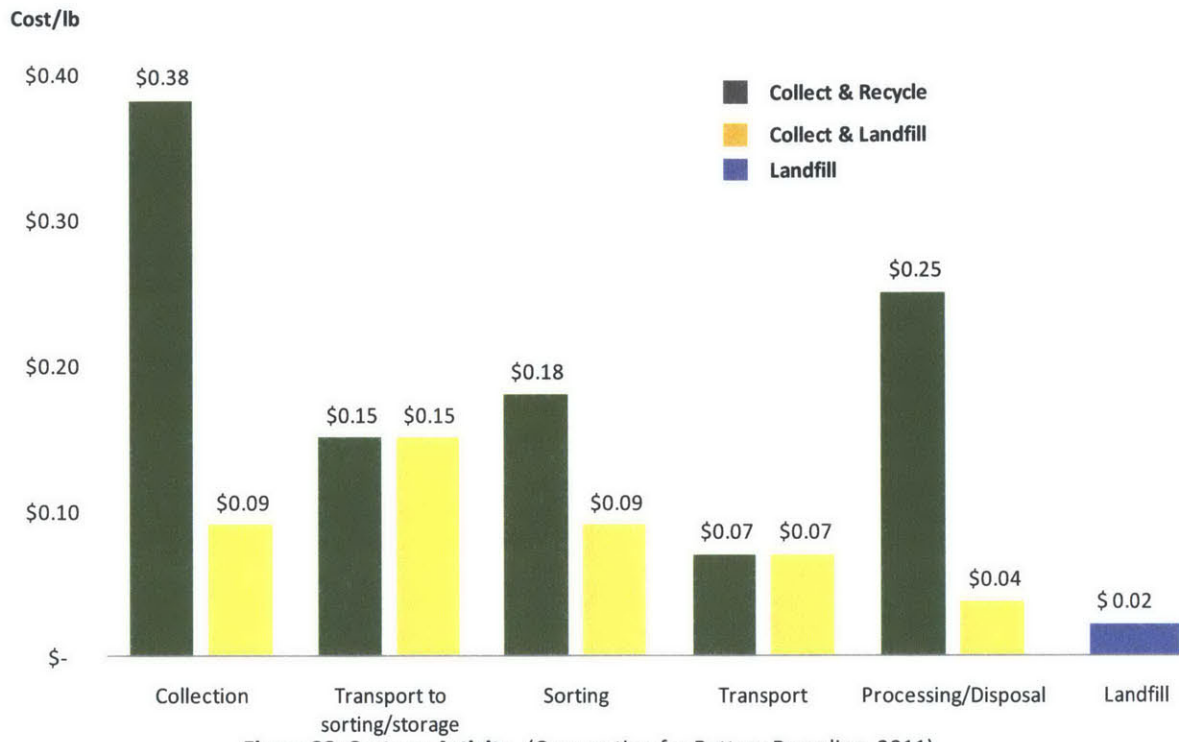


Figure 28: Cost per Activity (Corporation for Battery Recycling, 2011)

The largest cost differential for recycling versus landfilling is collection. This is because battery collection in the landfill scenario is assumed to be curbside, while a blended collection cost estimate is utilized for the recycling scenario consisting of retail drop-off (\$0.50/lb), curbside pickup (\$0.19/lb) and municipal drop off (\$0.26/lb)⁴⁹. The next largest cost differential is in processing/disposal, also known as recycling. While detailed cost information could not be found for each of the recycling options discussed, it can be argued the hydrometallurgical methods utilized by Battery Solutions may represent a cost advantage when compared to traditional pyrometallurgical methods. This cost advantage may be realized in two ways, the first of which being the much lower energy consumption of the hydrometallurgical processes in comparison with pyrometallurgy as shown in the GWP analysis. The second being the improved recovery of materials in the hydrometallurgical processes, which may result in greater revenues than pyrometallurgical battery recycling processes. Lastly, in the cost model shown in figure 30, a cost is assessed for transport from the sorting location to the recycling location. However in both the Call2Recycle and Battery Solutions networks, the majority of batteries are recycled in facilities in which sorting and recycling are co-located. Should battery collections increase

⁴⁹ (Corporation for Battery Recycling, 2011)

throughout the US and Canada, it may be advantageous to continue the practice of co-locating sorting and recycling processes.

All of the potential optimizations discussed in the paragraph above may be realized more readily with economies of scale. Curbside collection of waste batteries is not only the lowest cost collections alternative, but it is also the collection scenario that will drive the most collections and thus provide the most support in the development of economies of scale. Economies of scale may be realized in the recycling process through increased asset utilization (more uptime versus idle time), and stabilized and increased revenues due to improved predictability of recycling process outputs.

8 Conclusions

The current consumer battery recycling landscape in North America can be best characterized by two reverse logistics networks, the network that supports Call2Recycle and the Battery Solutions network. Understanding the composition by chemistry of spent batteries that are likely to be collected is critical to determining the global warming potential of each of these networks. As discussed, the global warming potential of the Battery Solutions network is nearly half that of the Call2Recycle network. Depending upon actual collection volumes, it is anticipated that this difference could range between 17 million and 51 million CO₂ equivalents per year. While this may seem like a significant difference, to put this in perspective, taking the greatest possible differential, this difference still equates to the CO₂ output of only 2,562 US citizens.

Though the term “logistics” may seem to imply transportation activities, the primary difference between the Call2Recycle and Battery Solutions reverse logistics networks is in the recycling methods utilized. Hydrometallurgical and pyrometallurgical recycling processes have been shown to differ greatly in energy requirements and material recovery. These types of processes may also differ in terms of costs, with the likely cost advantage provided by hydrometallurgical processes due to energy consumption considerations.

Implementing a reverse logistics network for consumer batteries will require a significant cost burden, perhaps up to 50 times greater cost than current landfilling methods. Through the use of mandated Extended Producer Responsibility (EPR) schemes, this cost will likely be borne by the manufacturers of these batteries. Similar EPR based reverse logistics networks have been implemented successfully in Europe and Japan. Though the current estimated costs are far greater than existing landfilling practices, there exist many opportunities to reduce the cost of the reverse logistics network. These opportunities include implementing the appropriate collection system, utilizing the ideal recycling methods, and realizing economies of scale.

As environmental consciousness continues to grow in the minds of consumers, the legislative landscape for consumer battery recycling in North America will continue to evolve. Traditional recycling legislation mandates “what” needs to be done, but typically fails to address “how”. As legislation is adopted throughout North America to create a broad consumer battery

reverse logistics network, it is important to consider how this reverse logistics network will be carried out in order to minimize the environmental impact and achieve the lowest possible cost. The extent to which environmental impact and cost can be managed successfully will likely determine the adoption rate and overall success of any future consumer battery reverse logistics network.

While recycling method was shown to be a major factor from a GWP perspective, future analyses should explicitly address the costs specific to these process. In the same regard, as collection volumes increase, future researchers will benefit from an idea of the economies of scale that may be realized in both cost and per unit environmental impact. Though it was demonstrated by the Battery Solutions network that a second sorting facility would reduce inbound transport, it was also demonstrated that additional recycling facilities would be necessary to realize the resulting cost/environmental benefits from an overall reverse logistics network perspective. Future analysis should consider the cost of additional recycling facilities and weigh this against the cost of transportation. There may be some combination of collection volumes and transport distances at which recyclers can financially justify investment into new recycling facilities.

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10 Appendices

10.1 Interviewee Profiles

10.1.1 Carl Smith – CEO, Call2Recycle

Carl Smith is the CEO of the aforementioned Call2Recycle organization. The bio statement that follows has been pulled directly from the Call2Recycle website.

...In this capacity, he oversees the organization's strategy, partnerships and management of its national promotion and education efforts, serving as a model for product stewardship. Working directly with its board of directors, Mr. Smith leads the overall direction of the company. He also serves on the board of directors for EPEAT, the worldwide sustainability standard for computers, printers and other electronics. Mr. Smith has extensive experience in strategic marketing, brand positioning, product / business development and environmental leadership. He previously served as the CEO of GREENGUARD Environmental Institute, a non-profit organization that develops and promotes indoor air quality standards and programs. Before that, he was a senior marketing and general management executive with a Fortune 500 company and served in various capacities on Capitol Hill⁵⁰.

10.1.2 Jeremy Sova – VP Account Management, Battery Solutions

Jeremy Sova is the Vice President of Account Management at Battery Solutions. In this role he is focused on customer (collection partners) acquisition and retention. He works to develop new programs that will help to drive additional battery recycling volume. He has a deep knowledge of the battery recycling industry having spent his entire 17 year career with Battery Solutions. This knowledge extends to the regulatory environment surrounding battery recycling as well as the various technologies and industry players involved in the field. In addition to the "official" years he has spent at Battery Solutions, Jeremy has been exposed to the business since its founding by his father and current CEO Chris Sova.

⁵⁰ (Call2Recycle, 2011)

10.1.3 Ivy Leimbach – Vendor and Compliance Manager, Batteries Plus

Ivy Leimbach is the Vendor and Compliance Manager for the Batteries Plus chain of retail stores. In this role she remains abreast of all legislative activity in the battery space that may have a material impact on the business. Since all Batteries Plus locations participate in some form of battery collection, Ivy has deep expertise in this area – particularly in terms of the cost of battery recycling alternatives for the retailer. Ivy has been with Batteries Plus for 14 years and has seen the role of recycler evolve within the retailer during that time.

10.2 Land Transport Indexes for Battery Solutions

Table 11: Derivation of the land transport weighted average – Howell, MI

Metropolitan statistical area	2010 Census	% weight	Distance from Howell, MI	Distance Contributed to Composite Index
New York-Northern New Jersey-Long Island, NY-NJ-PA	18,897,109	27%	643	171
Chicago-Joliet-Naperville, IL-IN-WI	9,461,105	16%	252	40
Philadelphia-Camden-Wilmington, PA-NJ-DE-MD	5,965,343	10%	612	61
Washington-Arlington-Alexandria, DC-VA-MD-WV	5,582,170	9%	552	52
Miami-Fort Lauderdale-Pompano Beach, FL	5,564,635	9%	1401	131
Atlanta-Sandy Springs-Marietta, GA	5,268,860	9%	740	65
Boston-Cambridge-Quincy, MA-NH	4,552,402	8%	759	58
Detroit-Warren-Livonia, MI	4,296,250	7%	55	4
Minneapolis-St. Paul-Bloomington, MN-WI	3,279,833	6%	658	36
St. Louis, MO-IL	2,812,896	5%	519	24
Tampa-St. Petersburg-Clearwater, FL	2,783,243	5%	1196	56
Baltimore-Towson, MD	2,710,489	5%	555	25

Weighted Average Distance = 724

Table 12: Derivation of the land transport weighted average – Mesa, AZ

Metropolitan statistical area	2010 Census	% weight	Distance from Mesa, AZ	Distance Contributed to Composite Index
Los Angeles-Long Beach-Santa Ana, CA	12,828,837	29%	389	112
Dallas-Fort Worth-Arlington, TX	6,371,773	14%	1065	153
Houston-Sugar Land-Baytown, TX	5,946,800	13%	1175	157
San Francisco-Oakland-Fremont, CA	4,335,391	10%	769	75
Riverside-San Bernardino-Ontario, CA	4,224,851	10%	339	32
Phoenix-Mesa-Glendale, AZ	4,192,887	9%	20	2
Seattle-Tacoma-Bellevue, WA	3,439,809	8%	1434	111
San Diego-Carlsbad-San Marcos, CA	3,095,313	7%	361	25

Weighted Average Distance = 668