

Life Cycle Assessment of Alkaline Battery Recycling

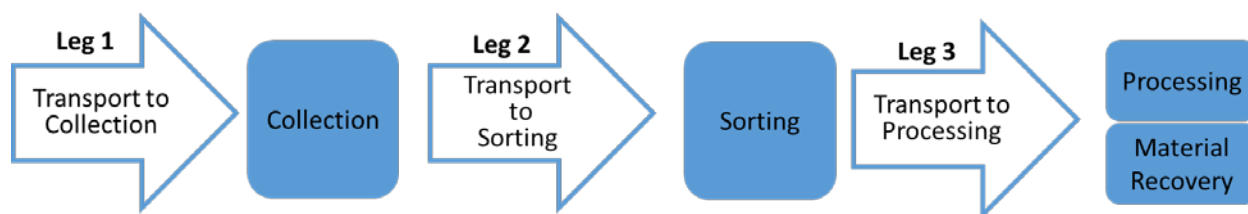
A report for the Corporation for Battery Responsibility

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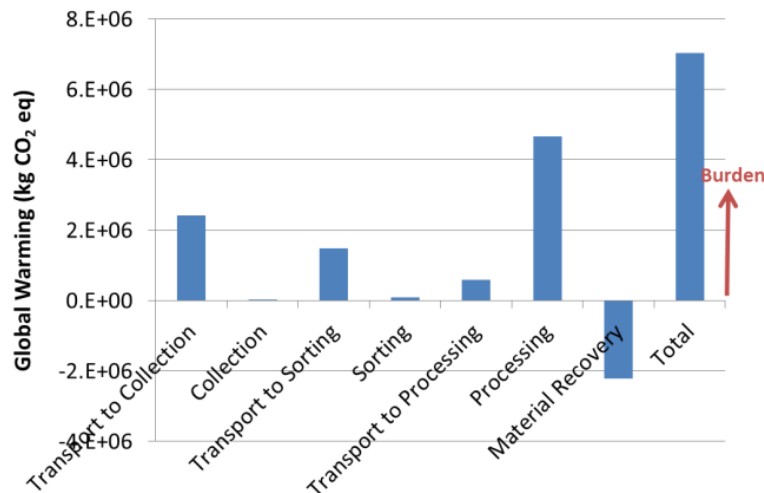
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Executive Summary

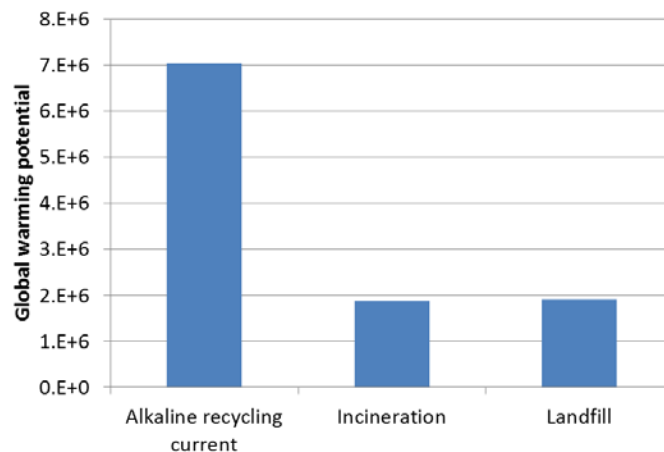
The objective of this study is to understand whether the benefits of material recovery from alkaline battery recycling in the US outweigh the burdens of collection and treatment. This is accomplished by conducting a life cycle assessment (LCA) of the current alkaline battery recycling system in the US using data on the performance of in-place collection and material recovery systems. This study combines data on the collection and treatment of alkaline batteries in the US in 2016 with data on transportation and treatment processes from studies in 2011 and 2012 that evaluated narrower scope recycling systems. The steps in the collection, sorting, and treatment process are outlined in the figure below.



The net environmental impacts of the US battery recycling system in 2016 were calculated using ten different environmental impact assessment and resource use metrics. The results for one of those metrics, global warming potential, are shown below, broken down by the end-of-life stages. A positive value in the chart is a burden, and a negative value is a benefit. The total quantity makes it clear that there is a net environmental burden for the US alkaline battery recycling system using the global warming potential metric. Similar net burden results were obtained for six other impact assessment metrics (including acidification and human health respiratory effects). However, three metrics (ecotoxicity, human health carcinogens, and human health non-carcinogens) showed a net benefit for the recycling system. This is driven primarily by the burdens of processing compared to the perceived benefits of material recovery.



The figure below demonstrates that the net impact for the current alkaline battery recycling situation is a burden and exceeds the strategies of incineration and landfilling by a factor of four for global warming potential; results are similar for six other metrics. However, the net impact for the current alkaline battery recycling situation is lower than incineration and landfilling of those same batteries for the metrics of ecotoxicity, eutrophication, non-carcinogenics and carcinogenics. For these metrics, recycling results in a net benefit relative to incineration or landfilling (or both). The benefit of recycling is driven by recovery of zinc for metal value and to a lesser extent for construction materials for these impacts.



Although several metrics show net environmental benefits of alkaline battery recycling, there is a focus in society on the greenhouse gas emissions of processes and hence, a net burden in GWP could be viewed as particularly problematic by some stakeholders. The key factors to reach net positive environmental impact can be divided into two categories. The first is the transportation impact, which is driven by the allocation of the fuel consumed by each trip and the distance of a trip. The second is the impact of processing, which is driven by the energy of the process and how much material is recovered and at what value. Driving towards lower energy, more efficient processes, or those that are not dedicated to battery processing could help reduce the burden of the processing step.

1 Introduction

The vast majority of alkaline (also known as single-use or primary) batteries in the US are disposed and sent to landfills or incinerators at end-of-life. Efforts to minimize waste disposal and associated policies to increase recycling efforts have led to questions about the environmental impacts of alkaline battery recycling. There are complex and uncertain potential impacts associated with placing alkaline batteries in landfills at end-of-life and although recycling may reduce those impacts, it may cause additional burdens that outweigh any perceived or actual benefits.

Principals at Camanoe Associates (who are also researchers at MIT) have developed models to calculate the net environmental impact of battery collection and recycling systems using life cycle assessment (LCA). The National Electrical Manufacturers Association (NEMA) supported a research effort at MIT to study the life cycle environmental impacts of alkaline batteries with a focus on end-of-life treatments; the results were published in 2011¹ (hereafter referred to as *the 2011 MIT study*). The study used generic recycling scenarios for collection and treatment since there were no alkaline battery recycling systems in the US at the time.

The Corporation for Battery Responsibility (CBR) commissioned Camanoe Associates to do follow-up analyses in 2012 of a specific collection and recycling system in Hennepin County (Minneapolis). The purpose was to understand how specific collection and sorting practices impacted net environmental impacts of the system. Results of these analyses were not published. Due to the contemporaneity of the 2011 report and the small scope (one county) of the 2012 report, results of these analyses were not published.

In the five-plus years since these studies have been conducted the alkaline battery recycling landscape in the US has changed in terms of scale but not in terms of processing technologies. Vermont has regulations covering alkaline battery disposal and recycling, and there are opportunities in many parts of the country to recycle alkaline batteries as part of rechargeable battery recycling systems. Thus, CBR commissioned Camanoe Associates to conduct an LCA of the current alkaline battery recycling system using contemporary data on the performance of in-place collection and material recovery systems, and the treatment destinations of the collected batteries. The purpose is to understand whether the net environmental impacts of the system may have changed over time as a result of changes in the system.

The 2011 MIT study contains extensive details on batteries, collection systems, recycling technologies, and LCA. This study builds off of that content and provides references where appropriate for the reader to consult it for further details, rather than duplicate the information here.

2 Summary Results of Previous Studies

2.1 2011 MIT study on generic recycling systems

The 2011 MIT study contained two components. The first was a whole life cycle assessment, which included the phases: materials production, battery manufacturing, packaging, transportation, and end-of-life (EoL). The functional unit for the analysis was 1 kg of a weighted average alkaline battery (WAAB). This is a single, hypothetical alkaline battery that is a weighted average of each size of battery (AA, AAA,

¹ E. Olivetti, J. Gregory, R. Kirchain, *Life cycle impacts of alkaline batteries with a focus on end-of-life*, 2011, https://batteryresponsibility.org/wp-content/uploads/NEMA_alkalinelca2011.pdf.

C, D, and 9V) based on percentage sales in 2007. This weighted average is used to determine the weight of the battery, the bill of materials, the amount of packaging and the weighted distance traveled in each transport step. A generic production and disposal or recycling scenario was used because data did not yet exist on a specific recycling system.

The key conclusion from the whole LCA was that *battery production dominates the life cycle environmental impact of alkaline batteries*, as can be seen in Figure 1. Battery production includes materials production, battery manufacturing, packaging, and transportation (i.e., everything except EoL). Within battery production, materials production represented the majority of the impact.

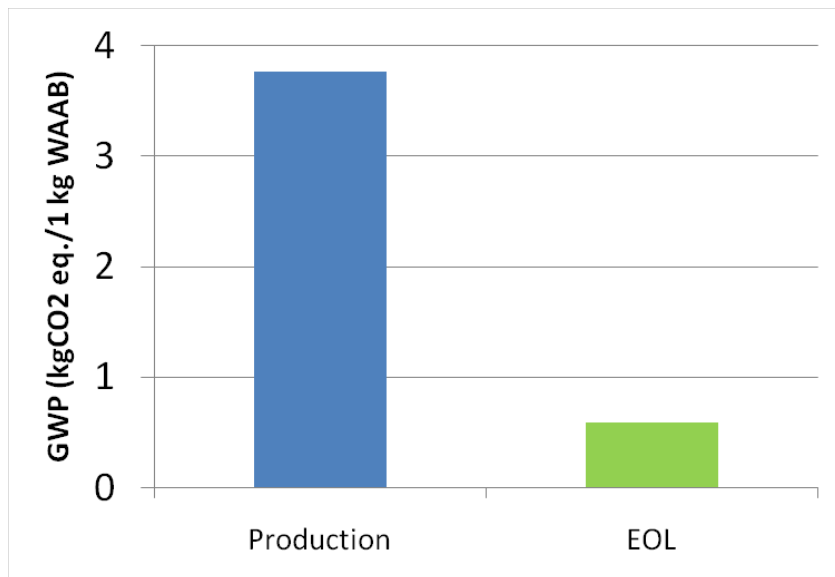


Figure 1. Life cycle global warming potential (GWP) of 1 kg of weighted average alkaline batteries including packaging. “Production” includes materials production, battery manufacturing, packaging, and transportation (i.e., everything except EoL).

Although battery production dominates the life cycle environmental impact, the second component of the 2011 MIT study was an in-depth analysis of the EoL phase because of the questions around the net environmental impacts. Several different scenarios were analyzed that varied collection, processing, and material recovery conditions. The scenarios are defined in **Table 1.**; details on the scenarios are in the 2011 study. Each scenario was compared against a baseline of municipal solid waste (MSW) collection and landfilling. Figure 2 is a schematic that demonstrates how all scenarios include elements for which there are burdens (e.g., collection and processing) and benefits (e.g., avoided material consumption) and a net impact is calculated from all of these elements. MSW scenarios always have a net burden because there are no material recovery benefits.

Table 1. Description of recycling scenarios used in 2011 study.

Scenario	Description	Materials Recovered
A	Metal fuming furnace;	Zinc (metal value); Steel and Manganese (cement/road construction)
B	Nickel reclamation furnace;	Steel (metal value); Zinc (metal value); Manganese (part metal value part cement/road construction)
C	Mechanical shredding and pulverizing;	Steel (metal value); Zinc/Manganese (micronutrient)
D	Electric arc furnace with steel recycling;	Steel, Zinc, and Manganese (metal value)
E	Aggregation of European pyrolysis and furnace processes;	Steel, Zinc, and Manganese (metal value)

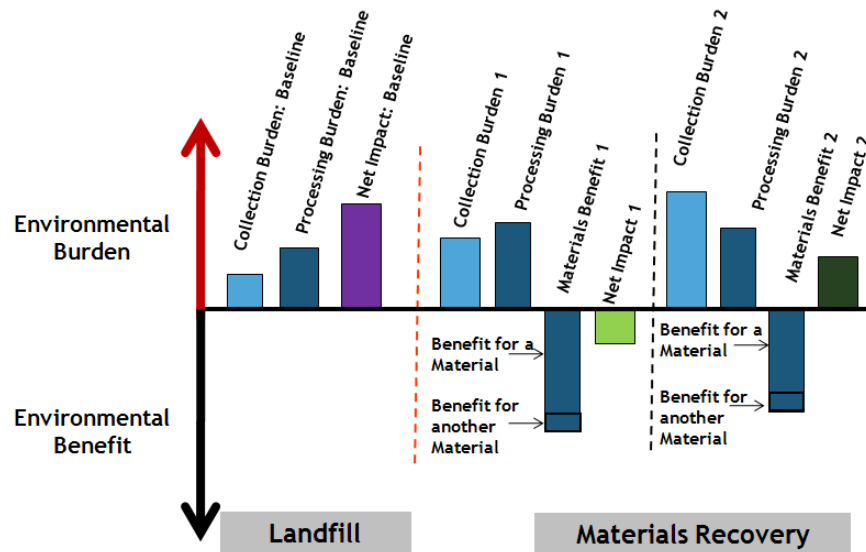


Figure 2. Environmental impacts of end-of-life treatment involves benefits and burdens. This schematic demonstrates how all scenarios include elements for which there are burdens (e.g., collection and processing) and benefits (e.g., avoided material consumption) and a net impact is calculated from all of these elements.

Five different environmental impact assessment metrics were used in the study: cumulative energy demand (CED), global warming potential (GWP), ecosystem quality, human health, and resources. Furthermore, five different scenarios of recycling were used (Table 1) that varied the types of technologies and recovered material destinations. Figure 3 shows that *net impacts for cumulative energy demand are higher than landfilling and incineration (MSW) for all of the recycling scenarios except 1*. However, *the collection mechanism has a significant impact on net impacts*. The results in Figure 3 are for batteries collected in retail stores where consumers have dropped them off. By contrast, the results in Figure 4 are for batteries collected at a municipal site where consumers have also dropped them off. There are greater impacts associated with the municipal drop-off and hence, the total impacts in Figure 4 are higher.

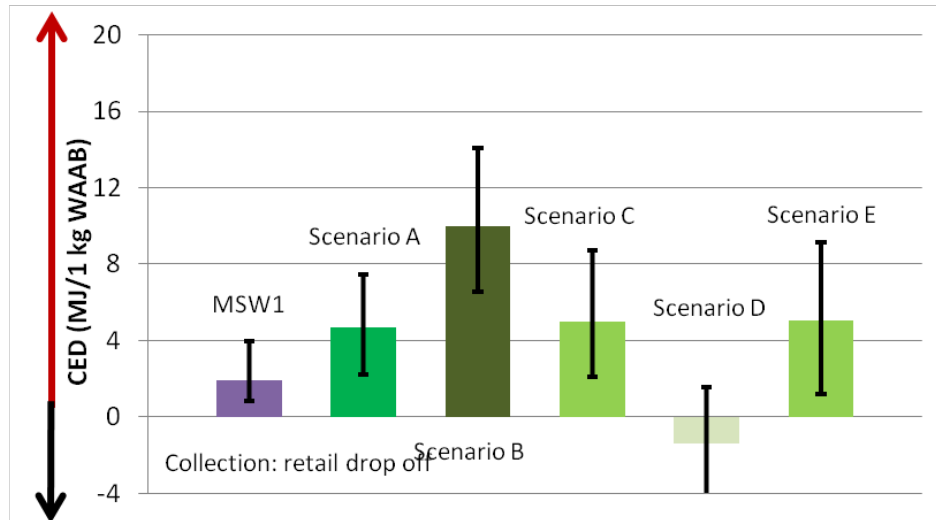


Figure 3. Cumulative energy demand of 1 kg of WAAB for MSW and five recycling scenarios. Collection scenario: *retail drop-off*.

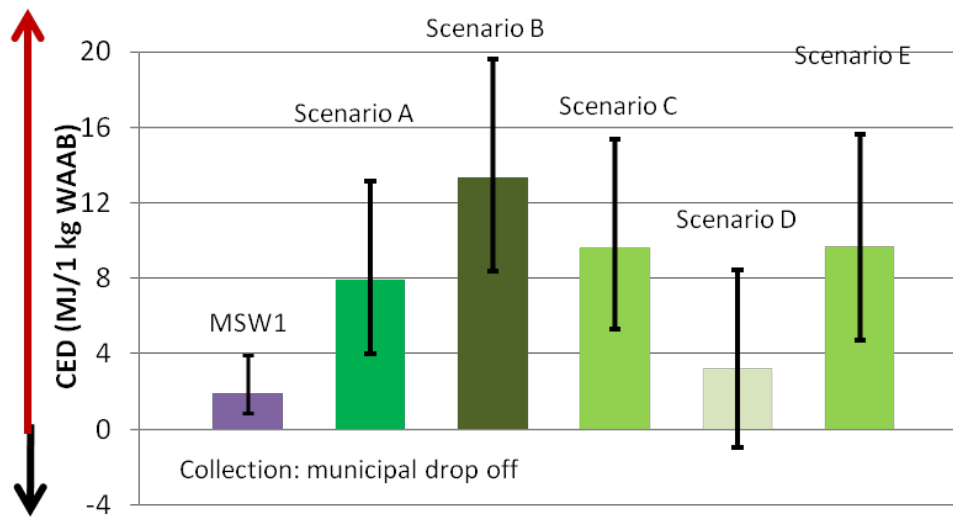
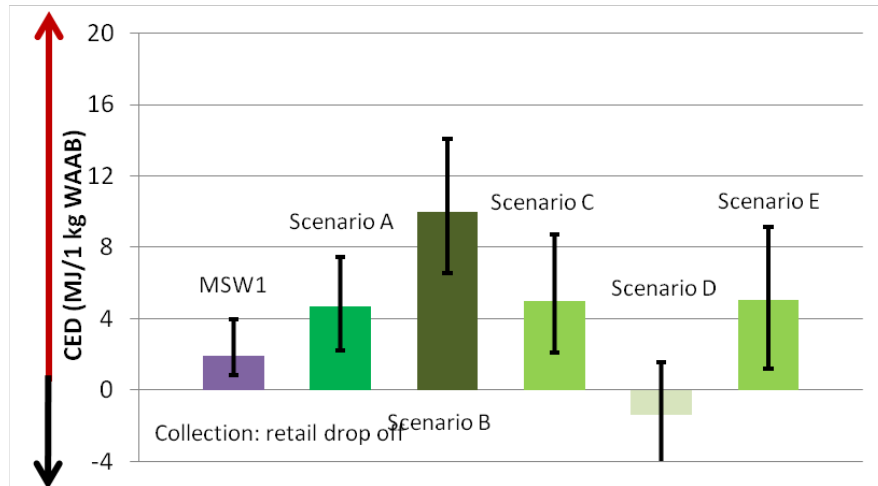
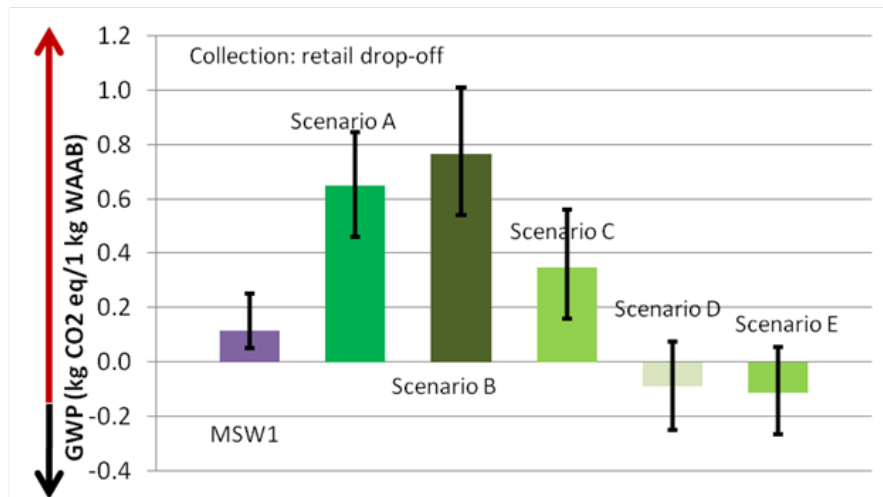


Figure 4. Cumulative energy demand of 1 kg of WAAB for MSW and five recycling scenarios. Collection scenario: *municipal drop-off*.

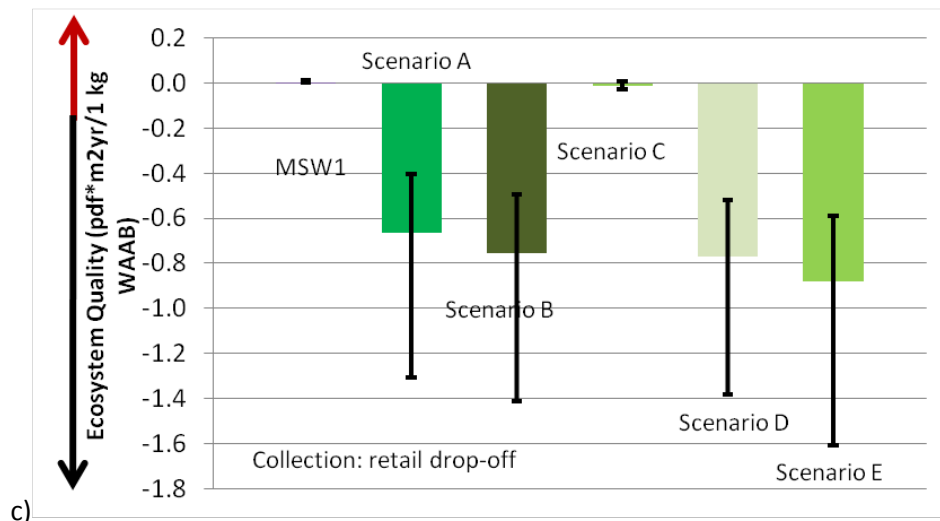
Although the results for CED showed recycling impacts higher than MSW impacts, *net environmental impacts depend on the impact assessment metric used*. Although CED and GWP have higher burdens than current MSW disposal for most of the recycling scenarios, the opposite is true for ecosystem quality and human health.



a)



b)



c)

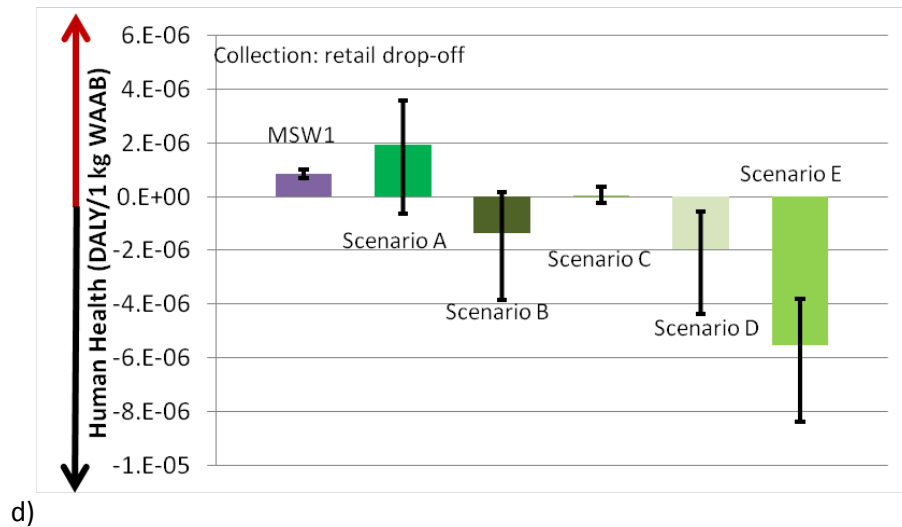


Figure 5. End-of-life environmental impacts of 1 kg of WAAB for MSW and five recycling scenarios using four different metrics: a) cumulative energy demand (CED), b) global warming potential (GWP), c) ecosystem quality, and d) human health.

In summary, the key conclusions from the 2011 MIT study on *generic* recycling systems are as follows:

- Materials production, rather than end-of-life disposal, dominates the life cycle environmental impact of alkaline batteries.
- Environmental impacts of end-of-life treatment involves benefits and burdens.
- Net impacts for cumulative energy demand are a burden and are higher than current MSW disposal for most recycling scenarios.
- The collection mechanism has a significant impact on net impacts.
- Net environmental impacts depend on the impact assessment metric.

2.2 2012 Camanoe Study on Hennepin's Recycling System

The Corporation for Battery Responsibility (CBR) commissioned Camanoe Associates to do follow-up analyses in 2012 of a specific collection and recycling system in Hennepin County (Minnesota). The purpose was to understand how specific collection and sorting practices impacted net environmental impacts of the system.

Figure 6 shows the scope of the study: collection, sorting, processing, and material recovery of alkaline batteries, with transportation legs in between. Data was collected on volumes of batteries collected in the system in 2010 by different collection mechanisms (e.g., retail, public, curbside, and events) and the specific sorting, processing, and material recovery solutions.

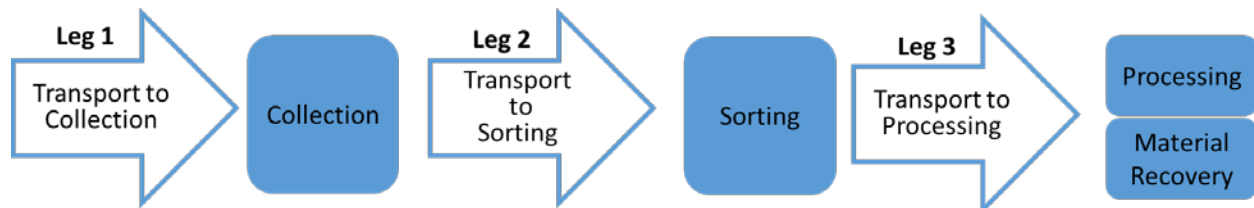


Figure 6. Scope of an alkaline battery recycling system.

Figure 7 shows the breakdown of the environmental impacts per kg of batteries processed for Hennepin County in 2010 for three different metrics (climate change, ecosystem quality and human health), along with the net environmental burdens for all three metrics. It is clear that there is a net burden for all three impacts and the first two transportation steps are driving most of that burden.

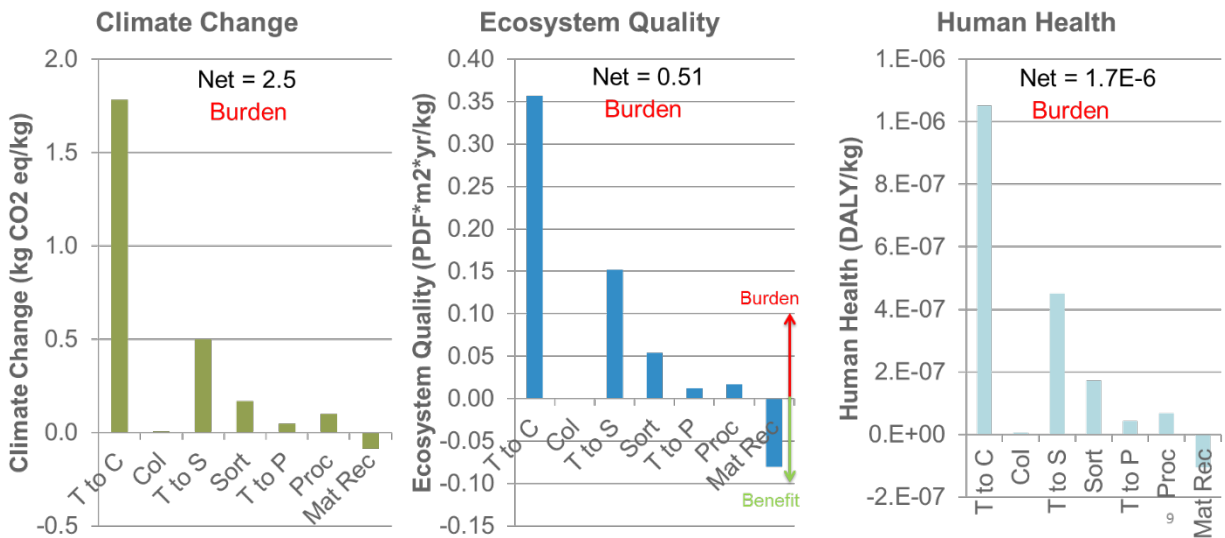


Figure 7. Environmental impacts per kg of batteries processed for Hennepin County in 2010 for three different metrics. Bars show impacts for different stages within the system: transportation-to-collection (T to C), collection (Col), transportation-to-sorting (T to S), sorting (Sort), transportation-to-processing (T to P), processing (Proc), and material recovery (Mat Rec). The net environmental burdens for all three metrics are listed on the charts.

The 2012 Camanoe study for CBR included some modeling analyses that explored the question of what it would take for Hennepin's system to be net environmentally positive. Recommendations were made in two key areas: transportation and processing.

Transportation:

- Reducing allocation of collection trips.
- Reducing distance from sorting to processing.
- Break-even distances calculated for all environmental metrics and processing techniques.

Processing:

- Mechanical processors piloting metal recovery beyond ferrous can become environmentally positive if zinc recovery can become quite high.
- Pyrometallurgical processors working towards process efficiency can become environmentally positive with significant efficiency improvements.

3 Goal and Scope

The goal of this study is to quantify the net environmental impacts of the US alkaline battery recycling system for one year. This is accomplished by updating the previous analyses using contemporary data on the performance of in-place collection and material recovery systems and the treatment destinations of collected batteries.

The 2011 study had a scope of generic recycling systems, and the 2012 study had a scope of Hennepin's recycling system in 2010. The scope of this analysis is the entire US alkaline battery collection and recycling system for the year of 2016, including representative collection and treatment flows from the system during the year. The process includes the steps detailed in Figure 6: from consumer to landfill/material recovery including transportation in between.

The functional unit for the analysis is all of the alkaline batteries collected and treated in the US in 2016. The chemistry of the batteries was assumed to be the same as the WAAB from the 2011 MIT study. Based on data collected from the firms processing the alkaline batteries collected in the US, approximately 3,700 metric tons of batteries were collected and recycled in 2016.

4 Methodology

This section describes the data sources and assumptions made within each segment of the end-of-life stage of the life cycle, following the steps detailed in Figure 6.

For the transport to collection phase (leg 1), this work was based exclusively on the analysis done in the 2011 MIT study with a distinction by each type of drop off location. All of this transportation was assumed to be by passenger car. Four types of collection points were used based on data provided by Call2Recycle, a battery collection and recycling program: manufacturing, business, public agency, and retail. For the retail and public agency locations the results of the modeling from the 2011 MIT study were similar. The assumptions were 9 km distance of travel, where 5% of the fuel burden was allocated to the trip for a retail collection point and 13% for a public agency collection point, so a higher burden associated with drop off at a public agency. For business and manufacturing locations, the distance traveled was 15 km with an allocation of 5% for both. An average amount of batteries transported for a consumer trip was 0.39 kg.

The modeling work for this leg of travel was done in the 2011 MIT study and summarized here. The average shopping trip as determined by the Department of Transportation is 14 miles. The range found in the literature was about 2 - 20 miles. In addition, distances were modeled using assumptions around population distributions in and around city centers to 600 of the existing Call2Recycle sites, predicting travel distances from 5-20 miles. These values vary as a function of population density with the shorter distances corresponding to more dense groupings of individuals. Several values in the literature provide some basis for the allocation number, which will vary by population density, nature of trip, season and amount of waste. The allocations for the retail drop off are lower than for the municipal drop off because often the retail destination lends itself to more potential other reasons for the trip, although the municipal drop-off trip is likely to include other similar recycling measures.

This study did not include any curbside pickup of primary batteries as the Corporation for Battery Responsibility indicated that curbside has not increased and in some cases has decreased in prevalence. The life cycle inventory (LCI) for the passenger car was the ecoinvent² dataset: *Transport, passenger car, petrol, fleet average*.

For the collection stage itself there are four types of locations: manufacturing, business, public agency, and retail. Within the collection facility the environmental impact of producing the container used to

² ecoinvent life cycle inventory database, <http://www.ecoinvent.org/>.

gather the batteries is accounted for. For each location the container was assumed to be made of plastic with a 5 year lifetime for all locations except for the public agency where the lifetime was estimated at 10 years. The container was assumed to be 8.6 kg for retail and manufacturing sites and 7.7 kg for public agencies and business locations. These data were based on the 2012 Hennepin study. The ecoinvent LCI inventory for the plastic was *Polyethylene terephthalate, granulate, amorphous, at plant*, and it was assumed to be processed via injection molding using *Injection moulding* inventory.

For the transport-to-sorting leg (leg 2), the data were based on sample data we received from Call2Recycle that we used to determine an average distance traveled. The data that were received from Call2Recycle included data for their top 100 collection sites for each of three sorting facilities including location, collection amounts, and site type, as shown in Figure 8. The sample that they provided covered 2.3% of Call2Recycle's alkaline collection and was broken down within the site types as shown below. The quantity of all alkaline batteries collected by Call2Recycle was less than 20% of the total number of batteries processed in 2016.

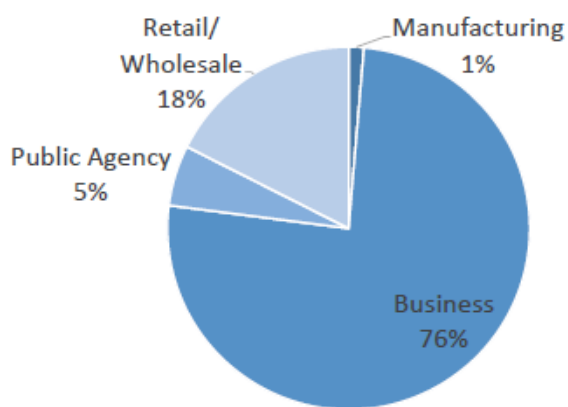


Figure 8. Breakdown of alkaline batteries collected by site type based on sample data from Call2Recycle.

The distance from each of the hundreds of collection sites to its corresponding sorting facility was determined using a distance calculator algorithm. The average collection-to-sorting distance by collection site type is shown in Figure 9. Given the similarity of distances in the network, the site breakdown may not be significant in assessing leg 2 impacts.

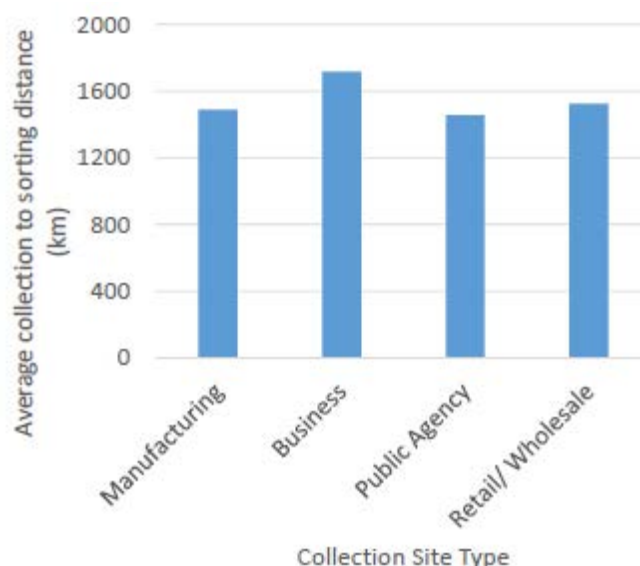


Figure 9. Average distance for collection-to-sorting facility by collection site type.

These values were scaled by the total quantity processed to quantify the total system impact for leg 2. This transport leg is assumed to be by large truck and the inventory used was the ecoinvent data set *Transport, lorry 16-32t, EURO3*. The total assumed weighted mileage for retail, public agencies, manufacturing, and businesses were 1,026,505 tkm³, 272,043 tkm, 55,644 tkm, and 4,880,167 tkm, respectively.

The sorting locations were Battery solutions in Howell, MI; Inmetco in Ellwood City, PA; and Wistron in McKinney, TX. The assumed sorting location consisted of an allocation of warehouse energy including electricity and natural gas consumption that was allocated by mass to the number of batteries sorted. There was also a metal container included for the sorting activities, but the impacts of the equipment used to do sorting was not included due to a lack of data on the subject. (Previous research on other processes has shown that such an assumption has a negligible impact on results.) The electricity was based on an average US grid mix. The LCI for the metal container was *Steel, electric, un- and low-alloyed, at plant* combined with the ecoinvent process *Steel product manufacturing, average metal working*, for the production of the metal container.

The transport-to-processing leg (leg 3) was based on knowing the final processing destination. The distance traveled ranged from 0-2000km (based on location, table shown below) and was by large truck using the LCI *Transport, lorry 16-32t, EURO3*.

Following the three transportation legs, processing consists of a processing burden for each of the three processing locations (the names are left out for data confidentiality) and then a credit assigned (where appropriate) for each processor. The data for one of the processors was updated between this study and the previous work, but we did not receive quantitative updated data from the other two processors. The final results were weighted by the amount of batteries processed at each location with a total of 3700 t as stated above.

³ tkm=ton-kilometers, using metric tons.

Data from the three processors that treat batteries collected in the system are summarized in Table 2, including materials recovered and assumed credits (these are the same first three scenarios defined in the 2011 MIT study). As with sorting, the impacts of the equipment used in the processes was not included due to a lack of data on the subject. Process A involves first a separation between magnetic and non-magnetic fractions. The non-magnetic portion then goes through a Waelz kiln process yielding two components: first, a crude zinc oxide that may be sold downstream to recover zinc through hydrometallurgical processes and second, and an iron rich material that goes into cement and road bed applications.

Process B involves a slag fuming furnace, which includes a charge stage whereby the cold, blended feed is metered into the furnace (along with the required amount of coal) and heated to approximately 1200°C. Each batch cycle with a cycle time of four hours consists of a charge stage, fuming stage and tap stage. The alkaline batteries (2-5 tons per 50 tons of feed) are charged to the furnace as whole batteries and not separated into components. Following the charge stage, the processing conditions are made reducing to fume Zn vapor, which is then re-oxidized in the gas space and condensed to solids in the boiler. The ZnO solids are moved to the baghouse for filtration with the solids collected and conveyed to downstream plants for further processing and Zn recovery. ZnO is first converted to ZnSO₄ in downstream leaching processes. At the end of fuming, the furnace bath is deficient in metal value and therefore the Mn oxide and steel with high yield remain with the tail slag, which is tapped with the granulated slag and then sold for cement manufacture. The furnace is fueled by coal, which is injected through tuyeres along with blast air and oxygen. The coal not only provides energy to maintain 1200°C bath temperature but also supports bath metallurgy in converting metals to their zero oxidation state, which then fume according to their high vapor pressures. The subsequent downstream processing of fume material yields 90% recovery of Zn to metal for market. The assumed electricity burden for subsequent product is modeled off of the Zn process wherein the Zn is then recovered from Zn electrolyte (H₂SO₄) at the Electrolytic and Melting plant. Hydroelectricity is used for the Zn recovery operation. The yields described by the company for this process are as follows: ~80% yield from the original amount of Zn and ~95% from the original amount of Mn and steel.

Process C involves electricity inputs to a mechanical shredding and pulverizing step that results in a fine particulate material. Steel is pulled off through magnetic separation prior to complete pulverization and sent to steel recycling. There is also a set of rinsing steps and natural gas inputs to a heating step (well below the melting temperature of the materials to drive off moisture). Zinc and manganese oxides are recovered to a micronutrient application for the agricultural industry. The recovered paper and plastic go to a waste to energy process. There is a lack of specific data on plant uptake of the micronutrients, so the assumption of 100% uptake would benefit from future research.

Table 2. Material recovery process descriptions.

Process	Materials recovered	Assumed credit
A	1. Steel 2. Manganese dioxide 3. Zinc	1. Metal value (market mix steel) 2. Cement/Road construction; Blast furnace slag cement 3. Metal value (market mix zinc)
B	1. Steel and manganese dioxide 2. Zinc	1. Cement/Road construction; Blast furnace slag cement 2. Metal value (market mix zinc)
C	1. Steel 2. Manganese dioxide and zinc	1. Metal value (market mix steel) 2. Micronutrient; fertilizer (100% plant uptake)

The processes for recycling were compared with data for landfill and incineration, which were developed in the 2011 MIT study (and not modified for this work). The baseline assumption was made for the municipal solid waste (MSW) disposal of alkaline batteries collected for landfill or incineration. The landfill and incineration inventories were developed for the 2011 MIT study and reproduced for this work. Details can be found in that document.

The life cycle impact assessment method used was TRACI 2.1, which stands for the Tool for the Reduction and Assessment of Chemical and Other environmental impacts. It was initially developed in the 2000s by the Environmental Protection Agency and collaborators. It particularly focuses on the US-context and was not used in the previous studies because it was not as well developed.⁴ TRACI has nine impact categories: ozone depletion, global warming, smog formation, acidification, eutrophication, human health carcinogens, human health non-carcinogens, human health respiratory effects, and ecotoxicity. Fossil fuel depletion is also characterized as a resource use.

5 Results

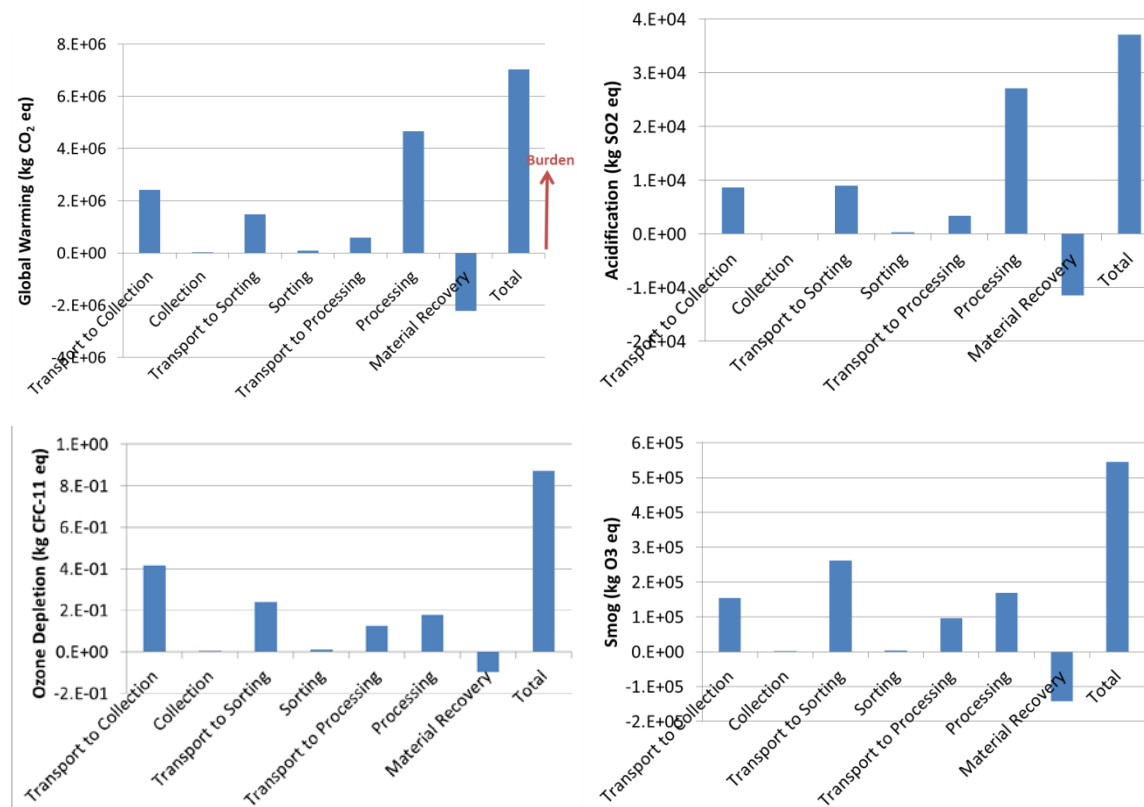
The first section of the results provides a breakdown across several TRACI midpoints for each end-of-life stage covered in Figure 6. This breakdown is shown in a series of bar charts where the three transport steps are delineated as well as the collection, sorting, processing burdens, as well as the material recovery benefit. The scope of the results include the entire US battery recycling system, with collection, sorting, and processing weighted by actual destinations for batteries. The total summed impact is also shown on the far right bar of each plot. The y-axes of each of the plots shown below in Figure 10 provide one of the TRACI midpoint categories; a positive value is a burden and a negative value is a benefit. The values of the y-axes vary in units and range for each of the categories and cannot be directly compared. Instead a decision maker may focus on the set of impacts that are most valued by interested stakeholders.

Several aspects of the analysis are consistent across all of the categories. For example, the burden associated with collection and sorting is a small portion of the total impact regardless of the category. The transportation impacts tend to decrease from left to right for all but one of the categories. This is because the degree of dedicated travel decreases as the batteries become more consolidated. As stated

⁴ Bare, J., [TRACI 2.0: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0](#). Clean Technologies and Environmental Policy 2011, 13, (5).

within the methods section the data for transport to sorting and to processing is scaled up from a small fraction of primary data from Call2Recycle. This may lead to inaccuracies in the second two transportation segments. The directionality of this inaccuracy is difficult to assess as some of the sources of error may underestimate more well distributed sorting locations, while others may overestimate extra crisscrossing of transportation between sorting and processing locations.

The largest difference across the impact categories is the burden of processing relative to the benefit of materials recovery. For global warming, acidification, and respiratory effects the burden of processing far outweighs the benefit realized, so that the total net impact for each of these categories is positive (representing a burden) and closely matched to this processing burden (plus the associated transportation impacts). This is dominated by the energy used in processing. In contrast, the impact categories including ecotoxicity, carcinogens and non-carcinogens have overwhelming benefit associated with materials recovery. This is driven almost exclusively by the perceived benefit of the recovery of zinc from the process (particular to processing scenario A). So for the recycling processes where zinc is not recovered for metal value this benefit will be less significant. Other categories including smog, fossil fuel depletion, and ozone depletion are more balanced between the burden of processing and the benefit of recovery, such that the total is driven by the transportation impact instead. Eutrophication is a bit different where the burden of processing is high, but so is the benefit of recovery, such that each of the segments of the end-of-life processing is significant (except for sorting and collection as stated above). For ecotoxicity there is benefit derived from zinc recovery, but also from the construction/roadbed application of certain materials. This variation in the trends between the impacts further underscores the importance of examining the categories independently so that this information is not lost.



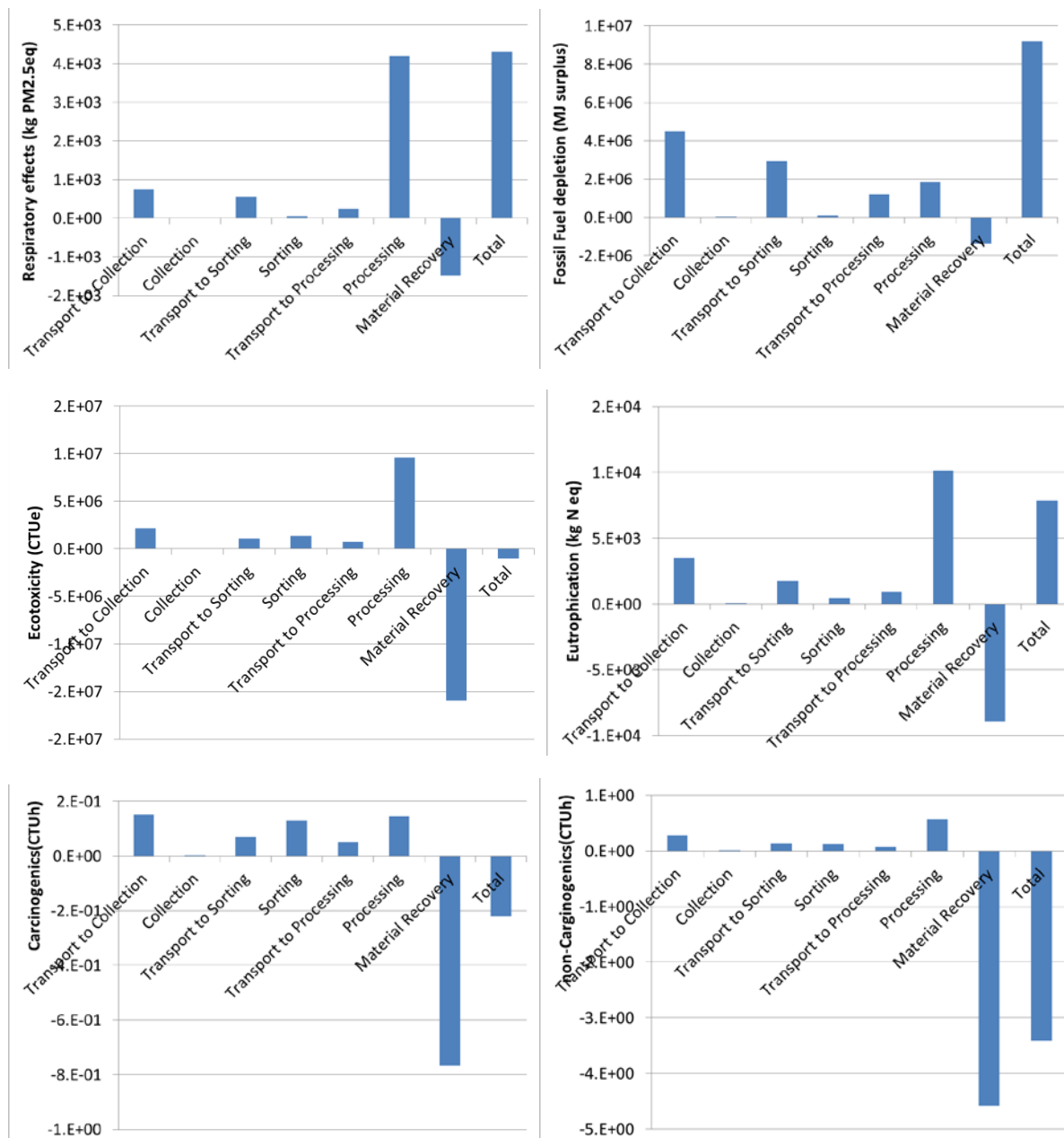


Figure 10. Breakdown of impact by segment for TRACI midpoint indicators (each midpoint shown in y-axis label). A positive value is a burden and a negative value is a benefit. The “Total” value is the net impact across the seven segments. The scope of the results include the entire US battery recycling system, with collection, sorting, and processing weighted by actual destinations for batteries.

The next set of results shown in Figure 11 demonstrate the net impact for the current alkaline battery recycling situation (as documented in Figure 10 above) compared with incineration and landfilling of those same batteries. For these two metrics the net impact of recycling exceeds that of incineration and landfilling by a factor of four for global warming potential and by a factor of twenty for acidification. Similar results were found for four of the other categories reported including fossil fuel depletion, respiratory effects, ozone depletion, and smog, where the impact of recycling exceeds that of incineration or landfill.

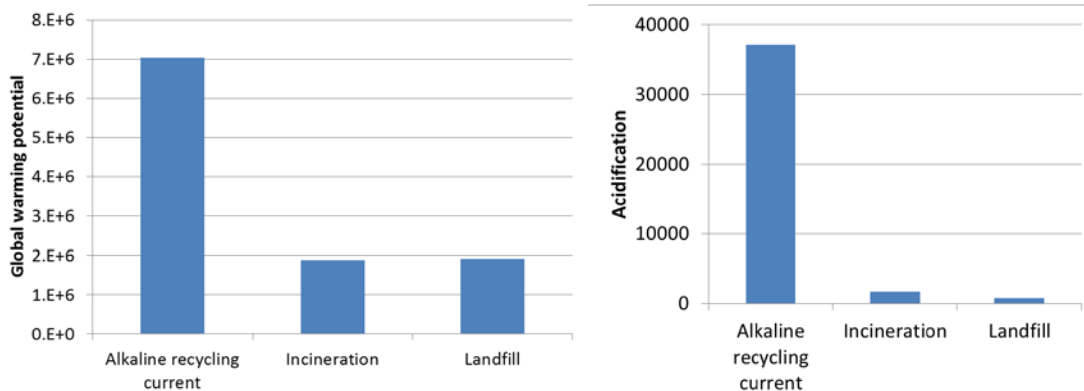


Figure 11. Comparison of net results for global warming potential and acidification for the current alkaline battery recycling situation with incineration and landfilling of those same batteries.

In contrast, Figure 12 demonstrates the net impact for the current alkaline battery recycling situation compared with incineration and landfilling of those same batteries for ecotoxicity, eutrophication, non-carcinogenics and carcinogenics. For these indicators recycling results in a net benefit relative to incineration or landfilling (or both). As described above, the benefit for the recycling is driven by recovery of zinc for metal value and to a lesser extent for construction materials for these impacts.

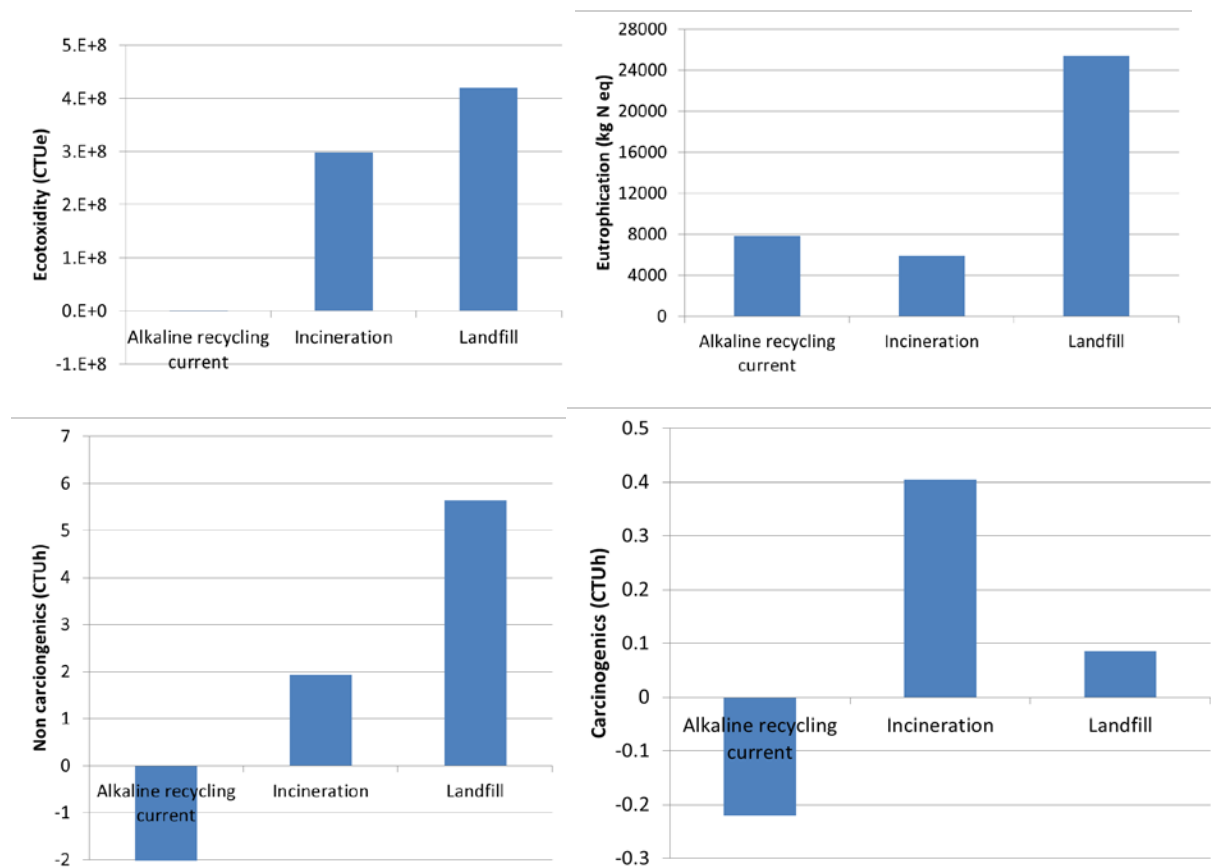


Figure 12. Comparison of net results for ecotoxicity, eutrophication, non-carcinogenics and carcinogenics for the current alkaline battery recycling situation with incineration and landfilling of those same batteries.

6 Conclusions

This study represents an evolution in analyses of battery recycling systems. The 2011 MIT study was an analysis of battery recycling using a generic, hypothetical recycling system. The 2012 Camano study was an analysis of one city's recycling system. This study is an analysis of the US alkaline battery recycling system using qualitative information from 2016 (with some limited updates of the data from the previous study where most critical).

The results show that alkaline battery recycling has a net environmental burden and that burden is higher than landfill or incineration impacts for the majority of indicators used in the LCA. However, two indicators show a net environmental benefit that is also lower than landfill or incineration impacts (which are net burdens): human health carcinogens and human health non-carcinogens. Ecotoxicity's net impact is approximately zero and is lower than both landfill and incineration. Eutrophication has a net burden and is higher than incineration, but lower than landfill. These findings that most indicators have a net burden and are higher than landfill and incineration are consistent with the findings of the 2011 and 2012 studies.

Although several metrics show net environmental benefits of alkaline battery recycling, there is a focus in society on the greenhouse gas emissions of processes and hence, a net burden in GWP could be viewed as particularly problematic by some stakeholders. The key factors to reach net positive environmental impact can be divided into two categories. The first is the transportation impact, which is driven by the allocation of the fuel consumed by each trip and the distance of a trip. The second is the impact of processing, which is driven by the energy of the process and how much material is recovered and at what value. Driving towards lower energy, more efficient processes, or those that are not dedicated to battery processing could help reduce the burden of the processing step.

6.1 Limitations

There are several key limitations to this work both in the area of data collection and also the area of uncertainty within these data. In the category of data collection only a small sample of sites and volumes collected were provided for this analysis. There are two ways in which this data set were limited, first in that the data only represented a small fraction of the total Call2Recycle data and second, Call2Recycle only collected around 20% of the alkaline batteries that were recycled in 2016. As stated above, this limitation likely leads to underestimate of transportation impact in some cases and an overestimate in others. Another key data limitation is around the processor data. For two of the processors new quantitative data were not obtained for this study relative to the 2011 MIT study. Rather these processors reviewed the data that were collected previously and commented on whether their process had changed. The analysts do not believe this decision would change the direction of the results for most of the impact categories as the difference between recycling and landfill/incineration is more significant than this data limitation in most cases. The exception to this would be impact categories such as eutrophication where the difference is more muted. Another key data limitation is the lack of specific data on plant uptake of the micronutrients resulting from process C (as well as the benefits of material use as fertilizer more broadly).

In the area of uncertainty within the analysis, it is difficult in particular to assign the "correct" allocation to the transportation of end-of-life batteries between a consumer and the drop off location. Also, as is typical of many life cycle assessment studies, there are significant uncertainties in the impact categories

particularly in toxicity and human health impacts. Those are more local indicators that would benefit from detailed regional model development that was outside the scope of this study.