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Economic Feasibility of a Mechanical Separation Process for Recycling Alkaline Batteries

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Abstract: *Spent primary alkaline batteries present an unused source of secondary metals in Europe and the US, with at least 300,000 metric tons of batteries being landfilled each year. While battery recycling programs exist, current hydrometallurgical and pyrometallurgical processes are not profitable when used for dedicated alkaline battery recycling, so industry growth is difficult. A novel mechanical separation process consisting of shredding, baking, magnetic separation, and specific gravity separation was developed to recycle one metric ton per hour of alkaline batteries at lower cost than current methods, while being environmentally beneficial. Financial analysis was conducted using a Process-Based Cost Model to address the challenges of modeling a recycling process. At full capacity, the cost to recycle alkaline batteries via the developed process is $529 per metric ton, +/- 25%, not including transportation, with revenue of $383 per metric ton. This cost is lower than that of other reported processes, but is still not economically feasible. With supplemental revenue of $0.3 per kg, which could come from various sources, the return on investment can occur in just under 3 years. The low value of alkaline battery recovery material is identified as the most significant economic barrier for the recycling.*

Keywords: Alkaline Battery Recycling, Cost Modeling, Economic Feasibility

1. INTRODUCTION

Nearly 80% of portable battery cells manufactured in the United States are primary alkaline batteries [1]. Additionally, 46% of all primary batteries sold in Japan and 72% of all batteries sold in Canada were alkaline batteries [2, 3]. Currently, the majority of alkaline batteries are disposed in landfills. However, unlike other types of battery waste, alkaline batteries are generally not considered to be hazardous. Neither the electrode materials nor the alkaline electrolyte are considered as harmful to the environment by the US Environmental Protection Agency [4]. Studies also shown that zinc and manganese from battery waste does not leach out of the battery in landfills [5].

Despite this, recent government legislations in the EU, Canada, and California have shown an interest in recycling alkaline batteries. New legislations have led to recycling rates for alkaline batteries of 10.15% in Canada in 2011 and 13.6% in the EU in 2009 [7, 8]and these rates are expected to increase in the next few years. This is because the avoidance of toxic chemicals entering into the waste stream is not the only impetus for recycling. Battery recycling can be ecologically beneficial by reducing landfill usage and recovering the materials for reuse [1, 6]. In addition, alkaline battery recycling can reduce the greenhouse gas emissions at the end-of-life as compared to landfilling [7]. These benefits are maximized by increasing reuse of materials, increasing landfill diversion, and by using a low energy process, e.g., not a melting process.

The construction and composition of spent alkaline batteries dictates the methods used for separation of battery components. Primary alkaline batteries are made up of a steel casing, manganese dioxide cathode with carbon added to increase electrical conductivity, zinc anode, potassium hydroxide electrolyte, a brass anode as a current collector, paper and nylon separator, as well as PVC used for a sealing washer and the label. The overall cell reaction is generally accepted to be $Zn + 2MnO_2 \rightarrow Mn_2O_3 + ZnO$, though this is simplified from what actually occurs, as many dif-

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ferent reduced manganese oxides are formed depending on the extent of the reaction [8]. Alkaline batteries come in many sizes, but for this research AA batteries were chosen due to their availability and because they are the most numerous form of alkaline batteries [9].

For a AA battery, the average composition identified is 37 wt% manganese dioxide, 23 wt% iron, 16 wt% zinc, 9 wt% water, 5 wt% potassium hydroxide, 4 wt% carbon, 2 wt% brass, and 4 wt% other, including paper and plastics [4, 8, 10, 11]. The existence of mercury is also possible, though it is a debated topic. All batteries have natural levels of mercury, though adding mercury to batteries is illegal in most developed nations. However, spent batteries from before these laws and counterfeit batteries may introduce added mercury into the waste stream. The existence of mercury has both been shown and disproven in a variety of published literature [8, 11, 12]. Perhaps most telling, many patents for alkaline battery recycling methods include methods for the removal of mercury [13, 14, 15]. Current methods of recycling these batteries include ways to remove the mercury from the process.

Hydrometallurgical and pyrometallurgical methods are used currently to recycle primary alkaline batteries. Hydrometallurgical processes use mechanical pretreatment to separate electrode powders from steel, paper, and plastics. In addition, baking is often used to vaporize mercury. The electrode powders are then dissolved in acid, and techniques such as electrolysis, solvent extraction, and precipitation are used to create high purity zinc and manganese end-products [16, 17]. Hydrometallurgical processing is conducted by companies such as Batenus, Recupyl, Recyctec, and Revatech [16]. Pyrometallurgical processing is generally done using existing electric arc furnace metal recovery techniques, separating iron, zinc, and manganese at temperatures exceeding 900 Celsius by volatilization and melt behavior [7, 18]. Pyrometallurgical processing is conducted by companies such as Batrec and Citron [6]. Hydrometallurgical and pyrometallurgical processes produce pure end products to maximize material value.

Although some companies have been able to successfully implement hydrometallurgical or pyrometallurgical processes, the growth of this recycling industry is hindered by the issues of transportation and recycling process cost. Collection and transportation of spent alkaline batteries can reduce or even wholly outweigh the environmental benefits of recycling, though curbside pickup and community drop off have been shown to be environmentally beneficial and financially feasible by various life cycle assessments [1, 3, 6]. Recycling process cost is a problem because no current process is profitable based on material revenue alone, therefore, requiring supplemental funding to make recycling possible. This is despite the efforts most recycling processes make to recover high purity products. Pyrometallurgical methods require large capital investment, since it uses large amounts of energy, and can produce air pollution. Hydrometallurgical methods are preferable as capital costs are lower and leachants can be recovered, but the cost is still too high for it to be a dedicated alkaline battery recycling process.

Reported recycling costs are mostly based on estimates and studies conducted by other researchers. Ferella reported a cost of about $1,000 USD per metric ton of batteries, while the Stewardship Ontario program reported cost for recycling was $2,948 per metric ton of primary batteries, but did include transportation costs [7]. The cost for recycling is then about $1,500 per metric ton, assuming half the overall cost is collection and transportation [1]. The difficulty in assessing the cost of a recycled material is due to the variation of the input and the control of the numerous outputs. In a simple production scheme, there is one product line. In the recycling industry there are many byproducts, which are all at different purities, quantities and qualities, making it almost impossible to use a linear cost analysis. A process-based cost model (PBCM) is instead used here to create models and not direct estimates of the possible revenue and costs of the recycling process. The limitations of the industry and the difficulty of cost estimates show that there is an opportunity for a purely mechanical process to reduce recycling cost, though at the expense of reducing end product value as well.

A mechanical separation process developed from background research and experimental results is shown in this work. The process has the goal of having a relatively low energy requirement and a high rate of landfill diversion, key factors for providing an environmental benefit to the alkaline battery life-cycle, as identified by several life cycle assessments. The developed process diverts 98% of spent battery material from landfill. 87% of the material is recovered for reuse. The process was not prototyped, but lab experiments verifying material properties and discussion with industry experts was used to guide process design. This process is then analyzed using the PBCM to determine the economics. The developed mechanical process is cheaper than any other reported process, though it is still not economically feasible due to low end-product value.

2. EXPERIMENTAL

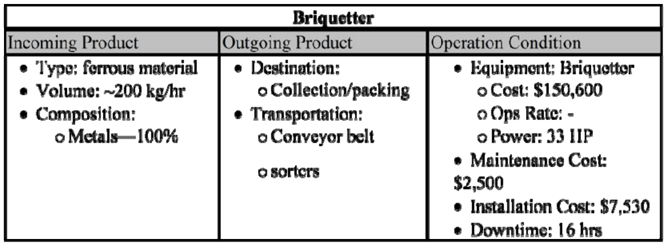
2.1. Battery materials characterization

Spent Duracell AA alkaline batteries were used for all experimental work. Batteries were dismantled by hand using a copper pipe cutter to examine construction and isolate the electrode powders. Energy-Dispersive X-ray Spectroscopy (EDS) and Scanning Electron Microscopy (SEM) tests were done to verify the electrode powder composition reported by other literature. EDS and SEM images were obtained using a JEOL JSM-7000F electron microscope. To examine the chemical and morphological changes that resulted during heating, the material was baked. From information gained through experimental work and from background research, a mechanical process was designed to separate battery components at a low cost.

2.2. Financial modeling

Financial modeling was done primarily using the techniques of a PBCM model [19]. This modeling employs special considerations to more accurately model costs and value for recycling processes. Modeling and cost estimation techniques from Perry's Chemical

Table 1. Operational model



Briquetter		
Incoming Product	Outgoing Product	Operation Condition
• Type: ferrous material • Volume: ~200 kg/hr • Composition: o Metals—100%	• Destination: o Collection/packing • Transportation: o Conveyor belt o sorters	• Equipment: Briquetter o Cost: $150,600 o Ops Rate: - o Power: 33 HP • Maintenance Cost: $2,500 • Installation Cost: $7,530 • Downtime: 16 hrs

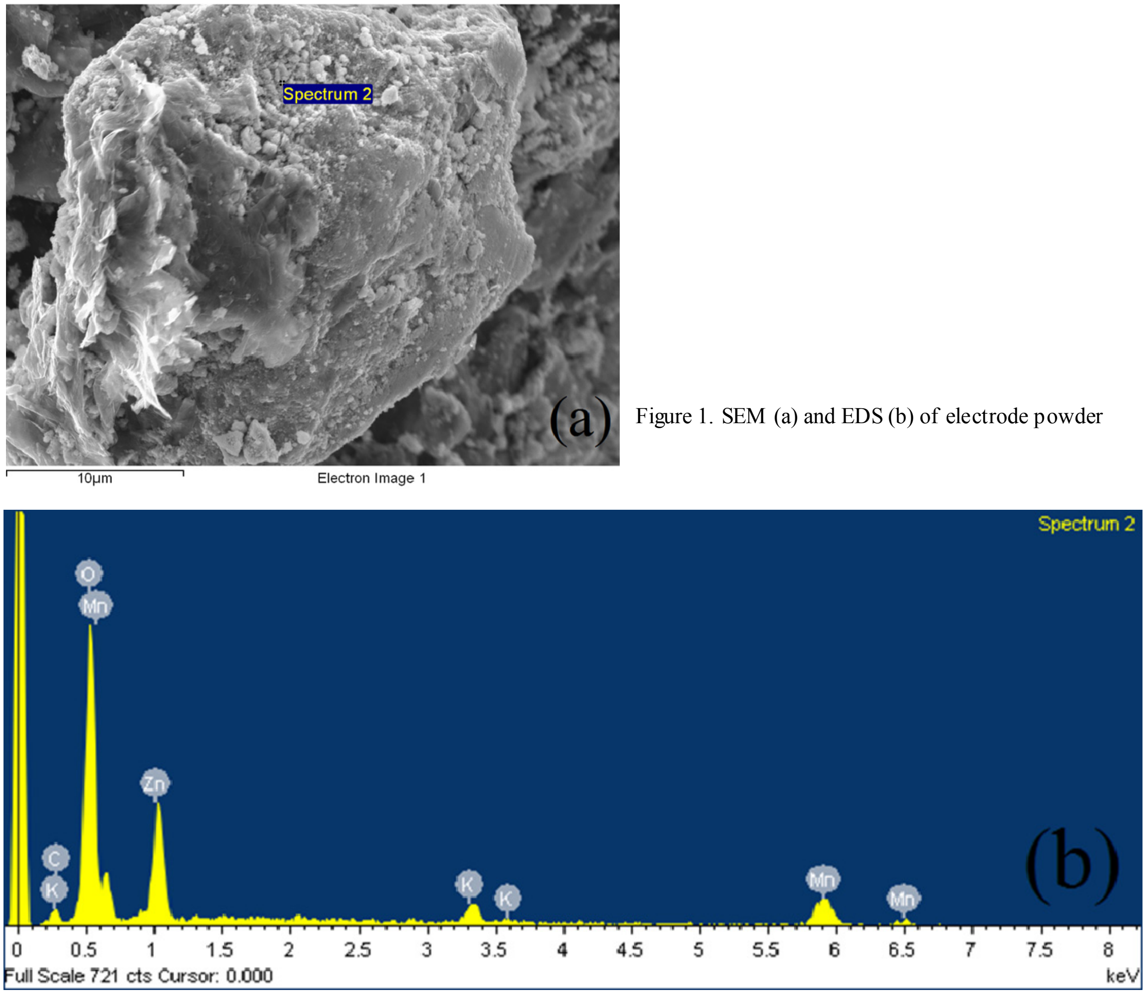


Figure 1. SEM (a) and EDS (b) of electrode powder

Figure 2. Spent anode exhibiting clay-like morphology

Engineers Handbook and from Technical Cost Modeling also aided the financial analysis [20, 21]. Equipment capital and variable costs were found by contacting equipment manufacturers for price quotes on actual products and by reviewing literature available for indexes and national estimates.

The cost model is divided into three main sections, the process model, operational model and the financial model. PBCM provides a framework for recycled materials, which is unique to other kinds of production. A recycling process includes more product streams than the regular production line. Thus, this financial model builds from the process model, which is the given process that will be used for the recycling. We then constructed an operational model, which considers workloads, value added, labor force required and processing throughput. An operational model was created for each of the equipments and a sample can be seen in Table 1. The operational model provides enough information to create a financial model that reflects the cost estimates of achieving the required recycling process.

3. RESULTS AND DISCUSSION

3.1. Battery composition

The results of dismantling tests, SEM, and EDS corroborate the battery construction and composition as described in the background. Results of EDS with SEM on the electrode powder, seen in Figure 1, verify the presence of zinc, manganese, and potassium.

3.2. Effect of baking on battery materials

Baking the battery material results in the dehydration of the electrode powder and the volatilization of mercury, as discussed in

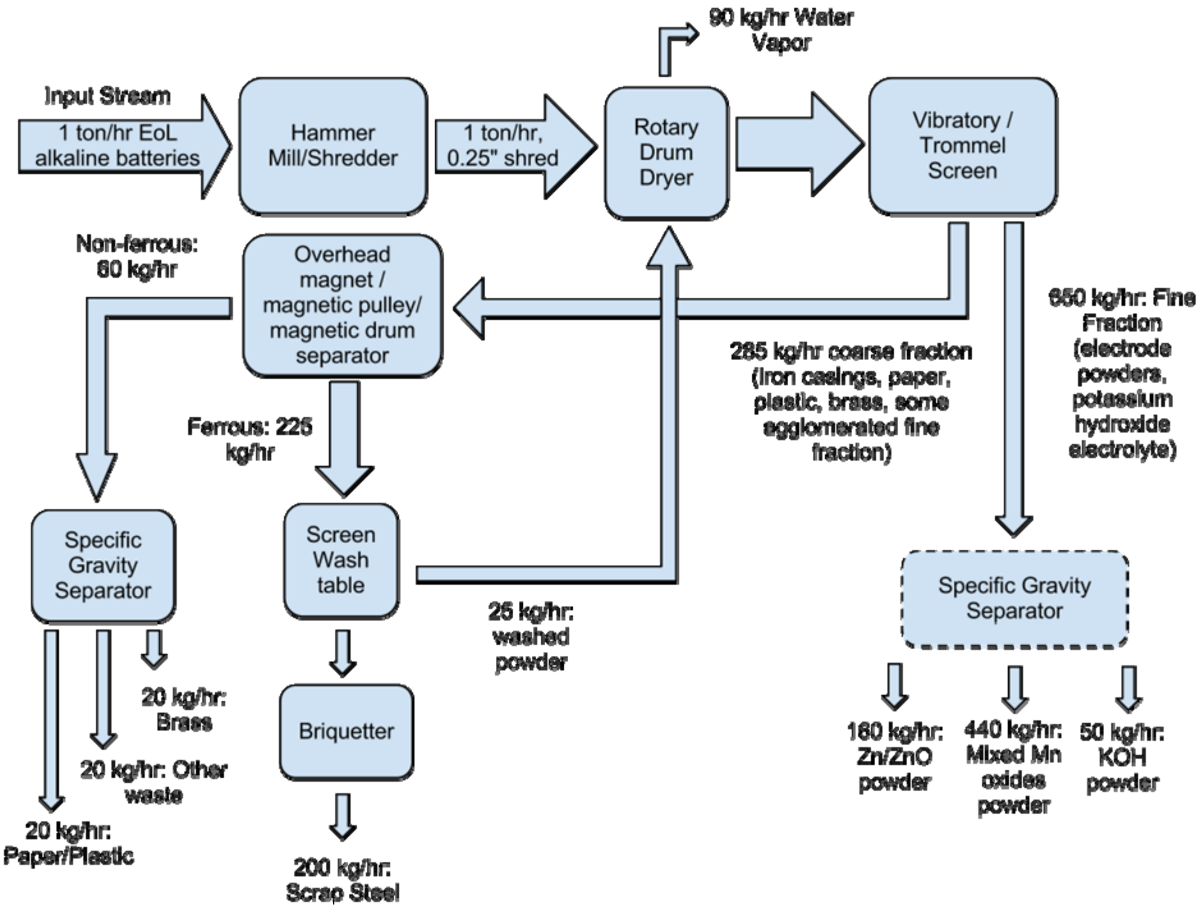


Figure 3. Mechanical separation process

Section 1. This is valuable because without baking the anode material it would be harder to remove anode material from the rest of the battery scrap, because the anode is clay-like before dehydration. The morphology of the spent battery anode can be seen in Figure 2. After baking at 425 Celsius for only 10 minutes, the anode dries and becomes a loose powder. While this baking does change the morphology of the anode, it is not hot enough to chemically reduce or vaporize the zinc. This baking also results in the formation of potassium hydroxide powder from both the anode and cathode materials. These dry powders are easily removed from other battery components by screening.

3.3. Developed mechanical separation process

The mechanical separation process developed is shown in Figure 3. The process assumes a constant input stream of one metric ton per hour of spent alkaline batteries. This process diverts 98% of battery material from landfill disposal. A total of 87% of battery material is recovered for reuse, while 2% is recovered for energy generation. The other mass losses are due to evaporated water from the batteries.

The process begins by passing batteries through a hammer mill where they are shredded so that all resultant particles are at most 0.635cm by 0.635cm. The shredded material is then transferred to a rotary drum drier, evaporating residual moisture and ensuring that mercury content is removed. The drier operates at 425 Celsius, with a hold time of 10 minutes. If the removal of mercury is not required, the oven can be used at lower temperatures, slightly lowering process cost by using less energy. Vaporized mercury is scrubbed via a carbon filter. About 90 kg of water will be evaporated from each ton of battery material. The dried material is put onto a 30 mesh vibratory screen to create a fine fraction and a coarse fraction.

The fine fraction consists of anode powder, cathode powder, and potassium hydroxide powder. This material can be directly sold as a fertilizer after the removal of mercury, or sold to the steel industry for metal value. It may be possible to separate these powders based on their densities using a specific gravity separator, allowing the powders to be sold as individual products, so this is how end product value is calculated in the financial analysis. Specific gravity separation is not tested experimentally in this work, however. Wet high intensity magnetic separation was also considered for the separation of zinc and manganese powders, but is deemed too expensive.

The coarse fraction consists of steel casings, paper, plastic, brass, and a small amount of agglomerated fine fraction powders. The coarse fraction is sent by conveyor belt underneath an overhead magnetic separator, which removes steel from the non-ferrous materials by magnetic behavior. As the steel chips are light, a permanent magnet can lift the chips from several inches above the belt, though the material stream on the belt must be spread. The steel is then washed to remove agglomerated powders, which are returned to the rotary oven. Steel is then briquetted to improve its value and remove any liquids. The remaining non-ferrous materials are separated from one another using a specific gravity separator. The brass is much denser than other remaining materials, while paper and plastics are less dense, allowing these to be separated with this equipment. Scrap brass can then be sold. Paper and plastics can be sent to a waste-to-energy facility so that they are diverted from the landfill. The 'other waste' left over from this separation may be scraps of paper or plastic with electrode powders left over, or simply unknown wastes, and can be safely disposed of in landfill.

Table 2. Revenue from end products

Material Sales Revenue

Product	Volume (kg/hr)	Market Price	Selling Price	Total Annual Revenue
Scrap Steel	**200**	**$ 0.10**	**$ 0.13**	**$ 54,080.00**
Paper	**10**	**$ -**	**$ -**	**$ -**
Plastic	**10**	**$ -**	**$ -**	**$ -**
Brass	**20**	**$ 1.80**	**$ 1.80**	**$ 164,736.00**
KOH	**50**	**$ 0.50**	**$ 0.50**	**$ 52,000.00**
Hg	**0**	**$ -**	**$ -**	**$ -**
Mn	**440**	**$ 0.43**	**$ 0.43**	**$ 393,536.00**
Zn/ZnO	**160**	**$ 0.18**	**$ 0.18**	**$ 131,788.80**
Other	**20**	**0.00**	**0.00**	**$ -**
			Total Revenue	**$ 796,140.80**
			Revenue/kg	$ 0.38
			Revenue/ton	$ 382.76

Table 3: Assumptions used in financial modeling

Type	Assumption	Sources
Tonnage	1 ton/hr 4160 tons/year	[7]
Conveyor belt price	$167.5 per ft., 50 ft. needed	[22]
Equipment maintenance	3% per year	[23] [24]
Equipment Depreciation	10 years	
Land Value	$40 per sq. ft.	[25] [26] [27]
Land Size	7,000 sq. ft.	[28]
Land Amortization	30 years	[29] [30]
Construction Cost	$59.5 per sq. ft.	[26] [31]
Construction Depreciation	25 years	[29] [30] [32]
Labor Cost	Depends on position	[33] [34] [35] [36] [37]
Janitorial Services	$210 per week	[38]
Benefits	30% over salary	[39] [40] [41]
Insurance	$2.5 per $1000 in sales	[42]
Taxes	10%	[43] [44] [45]
Scrap Batteries	$40 per ton	
Water	$1.5 per every 1,000 gallons	[46] [47] [48]
Electricity	$0.0935 per KWH	[49]

Table 4: Total cost for recycling process

Total Cost of Recycling Alkaline Batteries

Fixed Cost	per/year	Total Capital
Equipment Cost	**$ 61,685.60**	**$ 731,520.27**
Building Cost	**$ 25,993.33**	**$ 696,500.00**
Maintenance Cost	**$ -**	**$ 169,915.88**
Overhead Labor Cost	**$ 753,681.66**	**$ 693,681.66**
Installation Fee		**$ 31,261.55**
Total Fixed Cost	**$ 841,360.59**	**$ 2,291,617.81**
Variable Costs		
Material Cost	**$ 84,000.00**	
Direct Labor Cost	**$ 530,880.00**	
Utility Cost	**$ 377,650.21**	
Total Variable Cost	**$ 992,530.21**	
Total Process Cost	$ 1,833,890.81	**$ 3,284,148.02**
$/kg	$ 0.44	$ 0.79
$/ton	$ 440.84	$ 789.46

Process design was guided by experiments verifying the physical properties of the materials, analysis of the existing methods in literature, and discussion with industry experts from both alkaline battery recycling facilities and equipment manufacturers.

3.4. Financial analysis results

The value of the end products is $382 per metric ton. Most end product value information is from online scrap metal indexes, and the value of manganese powder is estimated from the market metal value. Table 2 shows the overall contribution of each material to the revenue stream.

Many assumptions had to be made to allow for the financial analysis to be accurate. The PBCM is based on a grass root factored estimate which gives the process a +/- 25 percent accuracy. These assumptions are shown in Table 3.

The results of the financial analysis concluded that the cost for recycling is $789 per metric ton. This is not including transportation costs. This reflects operations with 2 shifts at 16 hours per day. Table 4 shows a summary of the variables and fixed costs to operate at this rate for a year. The estimated total capital cost is then $2.29 million, with variable costs of $0.99 million.

At a specified tonnage of 4160 tons per year, using equipment specified to operate with an input stream of 1 ton per hour, the unit cost for recycling batteries is $0.79 per kg, while the unit revenue is $0.38 per kg. Therefore, this process is not economically feasible based on material revenue alone. Supplemental income of at least $0.41 per kg would be required to reach economic feasibility. Considering that the Stewardship Ontario program mentioned previously pays battery processors $1.24 per kg [7], this is reasonable. This cost is the lowest cost reported for the dedicated recycling of alkaline batteries.

Examining the model, the spread of the cost is dominated by the equipment cost, the building cost, and the overhead labor cost. The contribution of various factors to the overall cost can be seen in Figure 4. Because the operating costs from materials, direct labor, and utility count for only 30% of the total cost, there may be an opportunity to further reduce the cost of recycling by increasing the scale of the recycling process. However, this would need to carefully consider the effects of increased transportation needs, increasing overall cost and CO_2 emissions of recycling. If the vaporization of mercury is not required, the amount of energy used by the process can be reduced, though this would not have a significant impact on the economic feasibility since the rotary oven is still used to dehydrate the battery materials.

The cost of the process can be reduced without changing the scale of equipment by increasing the tonnage processed each year. The initial assumption was that the plant would operate 16 hours per day, 5 days a week. The analysis is extended to determine how increasing the operating time affects the costs. At a full uptime,

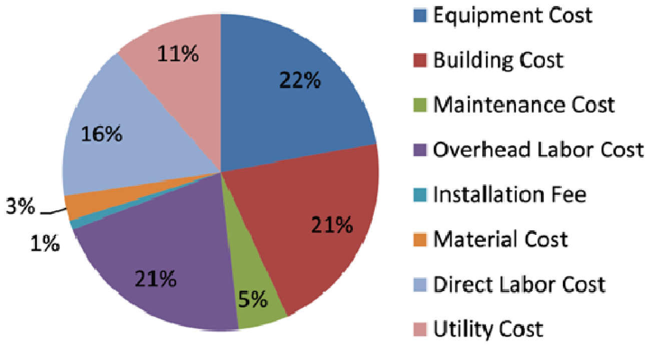


Figure 4. Overall cost breakdown

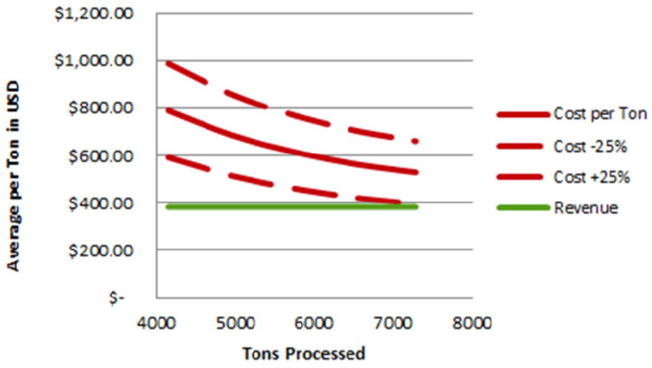


Figure 5. Scaling analysis

which is considered to be 20 hours per day, 7 days per week, the unit cost can be reduced to $529 per ton. While still not economically feasible, it is well under any reported costs for recycling of alkaline batteries. The supplemental income required for economic feasibility would then be $0.15 per kg instead of $0.41 stated above. Figure 5 shows how the process costs scales with tonnage, as compared with the revenue from the end products. At full operation capacity, assuming a supplemental income of $0.3 per kg, the process will have a return on investment time of just less than 3 years.

The uncertainty shown in Figure 5 reflects the 25% inaccuracy advised for factored estimates when using cost modeling. At absolute worst, the inaccuracy shows that this process is no more expensive than the best case found in literature. Even if there are difficulties in achieving high capacity in practice, the developed process is still cheaper per ton than published methods. At best, the developed process in nearly, but still not quite, financially feasible.

The difficulty in developing an economically feasible alkaline battery recycling processes is primarily due to the inherently low value of alkaline battery materials. Zinc, manganese, and iron are all plentiful and inexpensive materials, and it is difficult to increase the value of end-products without adding significant costs and processes. The raw material value of new alkaline batteries is about $1,600 per ton, estimated using metal and chemical price indexes, determining that this process only recovers about one-quarter of the material's original value. The recovered materials are much lower in value mainly due to their lower purity. For example, the manganese dioxide cathode material is produced via electrolytic deposition, resulting in greater than 99.9% purity. Recycled manganese oxides from alkaline batteries have a much lower inherent value, due to low purity, inconsistent oxidation state, and fewer commercial applications than the raw material. Similarly, the zinc product, composed of both zinc and zinc oxide, is at much lower purity than the original zinc powder, and cannot be improved easily. The most straightforward way to improve both these potentially high value materials is through electrolysis, the limits of which were mentioned in previous discussion on hydrometallurgical processes.

4. CONCLUSIONS

A mechanical separation process was developed for the dedicated recycling of alkaline batteries. This process used shredding, baking, screening, magnetic separation, and specific gravity separation to separate waste into distinct end-products. A Process-Based Cost Model was used to conduct a financial analysis. Transportation costs were not estimated. This analysis determined that the unit cost for recycling of alkaline batteries could be brought as low as $0.529 per kg, which is lower than any other reported costs for the recycling of alkaline batteries. However, the revenue from end products is only $0.383 per kg, so this process is not economically feasible based on end product revenue only. Given a 25% uncertainty in the cost model results due to the estimates made, the process is still promising: at worst, equal in cost to the best results found in the literature, at best, nearly financially feasible. The losses could be recouped by tipping fees, industry support, or government intervention. The motivation would be for environmental benefit, as numerous life cycle assessments have shown that low energy processes with high recovery rates, a standard by which this process was developed, are environmentally beneficial compared to landfill as well as pyrometallurgical processes.

Future work can be done to analyze the complexity interplay between the process scale and transportation costs. There is an opportunity to reduce cost by increasing scale, as the majority of costs are equipment and land related, so increasing scale should reduce cost. However, increased transportation would be required to consolidate greater amounts of batteries at a single facility, increasing cost and potentially reducing environmental benefit. Initial process prototyping and more thorough cost modeling can improve the quality of the results. By showing that the cost of alkaline battery recycling can be substantially lowered as compared to other reported costs, there is hope that mechanical separation processes can be established to increase alkaline battery recycling rates, creating new businesses and reducing the environmental impact of the alkaline battery.

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