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Life Cycle Analysis of AA Alkaline Batteries

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Abstract

From energy and CO_2 footprint perspectives, this study focuses on the Life Cycle Analysis (LCA) of AA alkaline batteries considering options other than landfill namely downcycling or, more ambitiously, recycling/remanufacturing. With the exception of lead-acid batteries that are recycled intensively in an energy-efficient manner, many types of batteries are not recycled and are disposed of via traditional disposal routes. Currently, there is lack of economical incentive given that available processes used in recycling batteries to reclaim metals require 6-10 times more energy than extracting/refining those metals from ores. Some processes (e.g., pyrometallurgical) require large capital investment and use large amounts of energy. For AA batteries, current recycling techniques involve 1) burning off the plastic wrapper, 2) batteries are shredded, and 3) melted where metals segregate into layers according to their respective densities, and 4) each molten metal layer is then collected.

This study addresses the feasibility of recycling alkaline batteries, as they are the most common dry batteries as well as being more benign as compared with other types such as lithium-ion or Ni-cadmium. From energy and CO_2 footprint perspectives, this study makes a case for downcycling or even recycling/remanufacturing (depending on the material of the separated components) for the zinc metal, manganese oxide concentrates, and other components for recycling/reuse in an efficient/environmentally-friendly manner. Life cycle analysis (LCA) findings suggest that, if technology is developed so that the cathode and anode materials are recycled/reused, there will be significant recovered energy and CO_2 values. For a world annual production estimate of 4 billion AA alkaline batteries, the EOL potential findings estimate energy savings and CO_2 footprint reduction of about $6.2*10^{15}$ J and $3.75*10^{8}$ CO_2 kg, respectively.

Keywords: Life cycle analysis (LCA); EOL potential; Alkaline batteries; Lithium-ion batteries; Carbon footprint; Energy consumption

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1. Introduction

No accurate data is available worldwide but more than 53 million dry batteries are discarded annually in landfills in Lebanon alone. Depending on the chemistries in each type, dry batteries may contain harmful chemicals such as cadmium, potassium, lithium, and mercury. Toxins are released into the air when the garbage is burned in waste incinerators. Furthermore, chemicals in batteries leach into the soil, groundwater, and surface water. Polluted water and crops are then consumed by animals and humans resulting in diseases such as liver and kidney damage leading up to cancer due to prolonged exposure to such chemicals [1]. Landfills in Lebanon are shutting down as they have been reaching their maximum capacity and currently no solutions are being proposed. Battery recycling organizations in Lebanon are currently shipping batteries overseas where recycling is not cost effective and may not be recycled ineffectively there.

With the exception of lead-acid batteries that are reclaimed and recycled intensively and in an energy efficient manner, many other types of batteries are not recycled and are disposed of via traditional garbage disposal routes. The costs of the recycling processes do not offer economical incentives given that current methods used in recycling batteries to reclaim metals require 6 to 10 times more energy than extracting / refining those metals from ores. Some of these processes (e.g., pyrometallurgical) require large capital investment and use large amounts of energy resulting in air pollution. As compared with other types such as Li-ion or Ni-cadmium, alkaline batteries are the most common and more benign dry batteries. For alkaline batteries, current recycling techniques involve at first burning off the plastic wrapper then the batteries are chopped off and melted where metals segregate into layers according to their respective densities. The molten metals will form layers according to their respective densities, skimmed off, and collected [2, 3]. One exception is lead-acid batteries where they are recycled intensively. In Lebanon, annually 4000 tons of lead-acid batteries are recycled by private companies.

This study conducts life cycle analyses in order to estimate the realized energy and CO2 footprint savings at end of life when scenarios other than landfill such as downcycle or even recycle become technically and economically feasible. Most salient compositions are the metal zinc and manganese oxide concentrates that require separating from metal and other components for recycling/reuse in an efficient and environmentally friendly manner.

2. Alkaline Battery- Construction and Material Composition

Performs, which are hollow cylinders made by pressing a granulated mixture of manganese dioxide, graphite and potassium hydroxide, are inserted in hollow nickel-plated steel cans. The combination of the performs and the steel can form the cathode. At the top of the can, an indentation is made which is sealed using asphalt or epoxy to avoid leakage. A porous synthetic fiber or a paper soaked (separator) in electrolyte is place inside the can and rests against the performs to separate the anode from the cathode and allow ion transfer. A gel comprising of zinc powder and potassium hydroxide is placed between the separator before the top of the can to allow for space when chemical reactions take place after the battery is sealed. At the negative terminal, a brass pin (current collector) is inserted through the anode in the middle of the can. Next a plastic seal is placed along with a metal end cap. The current collector is welded to the metal end cap. The other end of the battery is sealed using a steel plate glued with epoxy or welded. The paper label is glued to the battery or plastic which is heat shrunk [4]. Figure 1 (left) illustrates the internal structure of typical AA alkaline battery [4] while (right) shows the disassembled internal components (1) current pick up and negative terminal, (2) positive terminal, (3) manganese oxide powder cathode, (4) outer casing, (5) ion conducting separator, and (6) zinc powder anode.

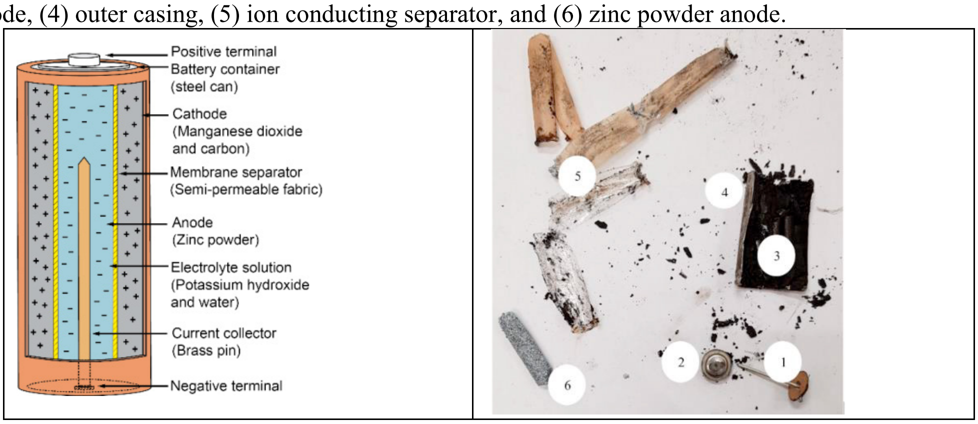

Fig. 1. AA alkaline Battery: (left) Internal Composition [4]; (right) disassembled internal components (1) current pick up and negative terminal, (2) positive terminal, (3) manganese oxide powder cathode, (4) outer casing, (5) ion conducting separator, and (6) zinc powder anode.

The weight of the resulting assembled AA alkaline battery is about 23 g. Table 1 lists the detailed materials list of 18 gr (not accounting for KOH of about 4 grams which is not available in CES Granta simulations below).

Table 1. Chemical composition by wt% of AA alkaline batteries [6]

Chemical	*wt%*	*total (23 grams)*
Lead	*<0.04*	*0*
Zinc	*16*	*3.68*
Manganese Dioxide	*37*	*8.51*
Carbon	*4*	*0.92*
Potassium Hydroxide	*17*	*3.91*
Nickel Plated Steel	*17*	*3.91*
Brass	*2*	*0.46*
Plastics	*1*	*0.23*

3. Alkaline Battery Life Cycle Analysis (LCA)- Whole AA Alkaline Battery

Using CES EduPack (from Granta Design), LCA (Level 3 Sustainability module [5]) was run to determine the relative effects through the use of the eco audit feature in the CES EduPack (Electrical components (ECO audit only option) offered by Granta design, a life cycle analysis has been conducted on a AA alkaline battery with mass of 23 gram (Figure 2).

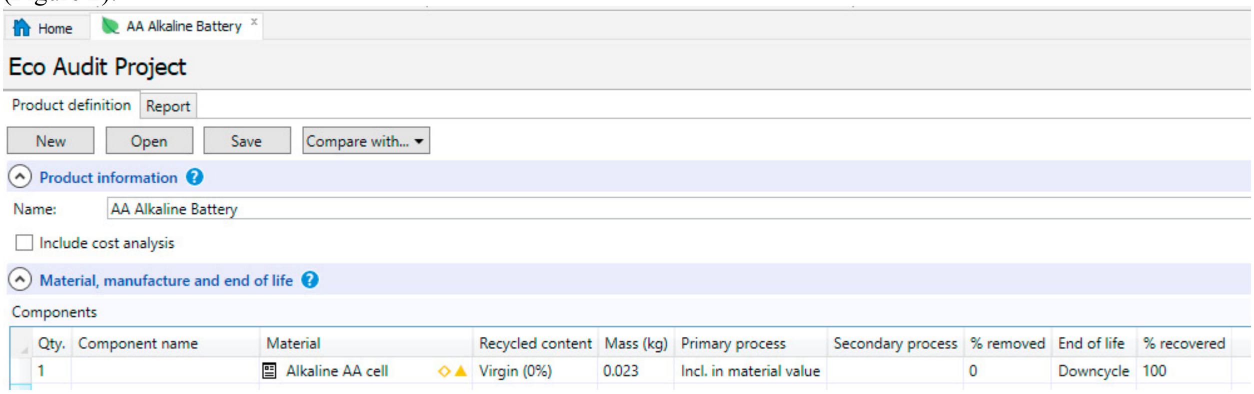

Fig. 2. Screen shot for AA Alkaline Battery eco audit in the CES EduPack (Electrical components -ECO audit only option)

Figure 3 shows the results of energy (MJ) consumed (left) and carbon dioxide footprint (right) for AA alkaline Battery as one unit in eco audit in the CES EduPack while only extracting the material. No account can be taken for manufacturing, transporting, use, and disposal. Energy saved and carbon dioxide emissions (kg) reduced at the end of the battery's life shown as end of life potential (per battery) are shown.

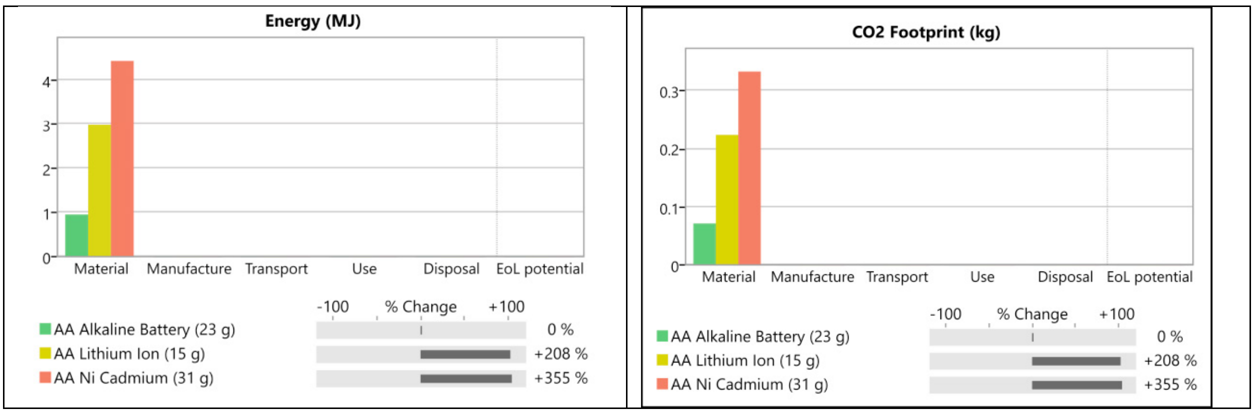

Fig. 3. AA Battery as one unit in eco audit in the CES EduPack: Energy (MJ) consumed (left) and carbon dioxide footprint (right).

An interesting comparison is made for the materials embodied energy for AA batteries: alkaline (23 g), Lithium ion (15 g), and Ni Cadmium (31 g) where the results of energy and carbon consumed are listed in Table 2.

Table 2. Energy and carbon consumed are compared for AA batteries: alkaline (23 g), Lithium ion (15 g), and Ni Cadmium (31 g).

AA Battery	Alkaline	Lithium ion	Ni Cadmium
Energy (MJ)	.965	3	4.43
CO_2 (Kg)	0.0724	0.225	.332
End of life potential Energy (MJ)	Option not available	Option not available	Option not available
End of life potential CO_2 Footprint (Kg)	Option not available	Option not available	Option not available

4. Alkaline Battery Life Cycle Analysis (LCA) w/ EOL Potential: AA Alkaline Battery separated components

Each component of the individual battery is input to CES software (Figure 4) along with its manufacturing process (if any) and transport. The program does not take into consideration the assembling of the final product. Finally, the program produces a report containing the carbon dioxide footprint and energy used at each stage along with the end of life potential. In addition to manufacturing and transport, embodied energy (MJ) is accounted for each component. Also, the end of life (EOL) of each component is inputted. CES returns energy (MJ) and CO2 footprint (kg) values.

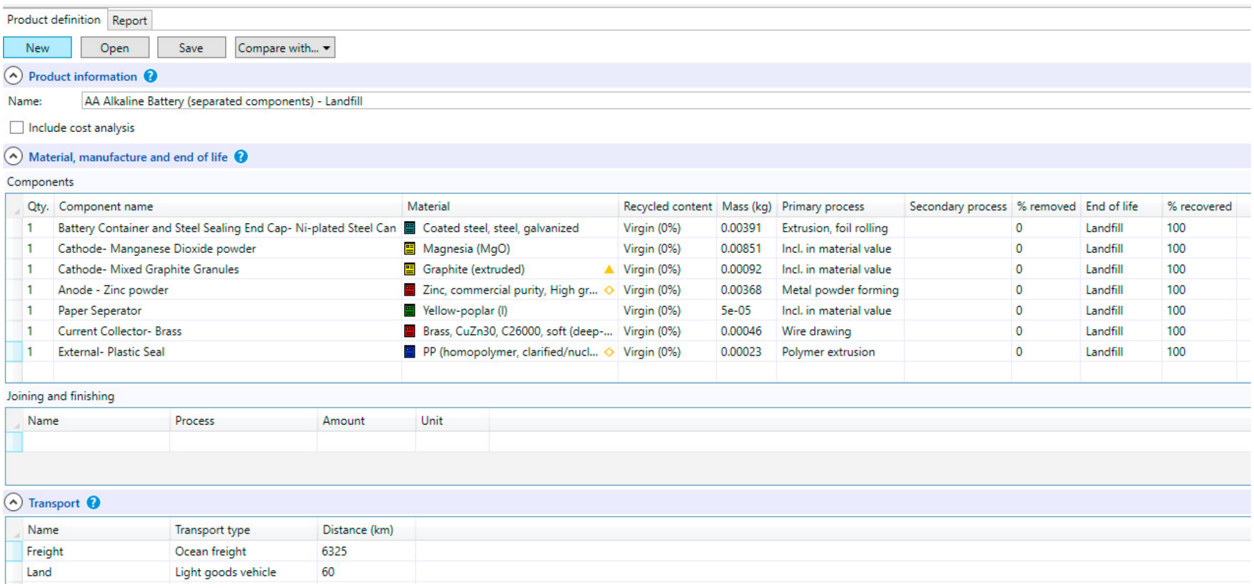

Fig. 4. Screen shot for AA Alkaline Battery eco audit in the CES EduPack for segregated components.

Of the components that make up the AA alkaline battery, most can be found in Level 3 Sustainability of CES Granta. However, some of the more challenging granulates that make up the cathode (manganese dioxide powder) could not be found in the database and had to be substituted with another oxide (Magnesia or Magnesium oxide). Other trials were made to also substitute with manganese metal but not much difference in materials embodied values were found. Transport is specified as freight via sea cargo (from source to country 6325 km) and local land transportation via light vehicle (60 km). the LCS analysis was run two ways: one as landfill option, downcycle, and recycle. For landfill option, the energy MJ value of combined material (1.65 MJ), manufacture (0.063 MJ), and transport (0.022 MJ) add up to **total of 1.73 MJ per AA alkaline battery** (compare with .965 MJ in previous section). The detailed breakdown of the material embodied energy are shown in Table 3. Similarly, the CO2 footprint (kg) value of combined material (0.1 kg), manufacture (0.0049 kg), and transport (0.0016 kg) add up to **total of 0.107 CO2 kg per AA alkaline battery**. By far, the largest portion of the energy consumed and carbon dioxide produced during the life of AA alkaline battery happens when extracting/processing the materials required to manufacture this battery (i.e., embodied energy).

Table 3. Energy spent for each AA battery as listed by material, manufacture, and transport, and disposal. Landfill option (no EOL)

Phase	Energy (MJ)	Energy (%)	CO2 footprint (kg)	CO2 foot print (%)
Material	1.65	94.8	0.1	93.6
Manufacture	0.0635	3.7	0.00495	4.6
Transport	0.0226	1.3	0.00162	1.5
Use	0	0.0	0	0.0
Disposal	0.00355	0.2	0.000249	0.2
Total (for first life)	**1.73**	**100**	**0.107**	**100**
End of life potential	0		0	

The breakdown of these aggregate MJ values above in Table 3 are listed by component in Table 4 which shows the largest % values are due to the cathode and anode powders.

Table 4. Energy spent for each AA battery as listed by each component. Landfill option (no EOL)

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Battery Container and Steel Sealing End Cap- Ni-plated Steel Can	Coated steel, steel, galvanized	Virgin (0%)	0.0039	1	0.0039	0.16	9.5
Cathode- Manganese Dioxide powder	Magnesia (MgO)	Virgin (0%)	0.0085	1	0.0085	1.1	65.3
Cathode- Mixed Graphite Granules	Graphite (extruded)	Virgin (0%)	0.00092	1	0.00092	0.2	12.3
Anode - Zinc powder	Zinc, commercial purity, High grade, min. 99.9%	Virgin (0%)	0.0037	1	0.0037	0.17	10.3
Paper separator	Yellow-poplar (l)	Virgin (0%)	5e-05	1	5e-05	0.00061	0.0
Current Collector- Brass	Brass, CuZn30, C26000, soft (deep-drawing/cartridge brass)	Virgin (0%)	0.00046	1	0.00046	0.025	1.5
External- Plastic Seal	PP (homopolymer, clarified/nucleated)	Virgin (0%)	0.00023	1	0.00023	0.016	1.0
Total				**7**	**0.018**	**1.6**	**100**

The breakdown of these aggregate CO2 footprint values are listed by component in Table 5 that shows the largest % values are due to the cathode and anode powders.

Table 5. CO2 footprint for each AA battery as listed by each component. Landfill option (no EOL)

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	CO2 footprint (kg)	%
Battery Container and Steel Sealing End Cap- Ni-plated Steel Can	Coated steel, steel, galvanized	Virgin (0%)	0.0039	1	0.0039	0.012	11.7
Cathode- Manganese Dioxide powder	Magnesia (MgO)	Virgin (0%)	0.0085	1	0.0085	0.058	57.7
Cathode- Mixed Graphite Granules	Graphite (extruded)	Virgin (0%)	0.00092	1	0.00092	0.015	15.2
Anode - Zinc powder	Zinc, commercial purity, High	Virgin (0%)	0.0037	1	0.0037	0.013	13.3

	grade, min. 99.9%						
Paper separator	Yellow-poplar (l)	Virgin (0%)	5e-05	1	5e-05	3e-05	0.0
Current Collector- Brass	Brass, CuZn30, C26000, soft (deep-drawing/cartridge brass)	Virgin (0%)	0.00046	1	0.00046	0.0017	1.7
External- Plastic Seal	PP (homopolymer, clarified/nucleated)	Virgin (0%)	0.00023	1	0.00023	0.00041	0.4
Total				**7**	**0.018**	**0.1**	**100**

The LCA with End-of-Life potential was also run for options other than landfill namely downcycle, and recycle / re-manufacture depending on the material (Figure 5). Although research is just starting on how to recycle or, better, reuse the manganese dioxide. The end of life potential of the AA alkaline battery more salient components are those of the cathode and anode materials. Currently there are no commercial methods to recycle manganese dioxide powder. The EOL values reported here are based on assuming of these other EOL options, however, the metal (steel, zinc) and plastic components of the battery are recyclable. Separated components of AA Alkaline Battery weigh 23 gr = 18 gr + 4 gr KOH (not considered).

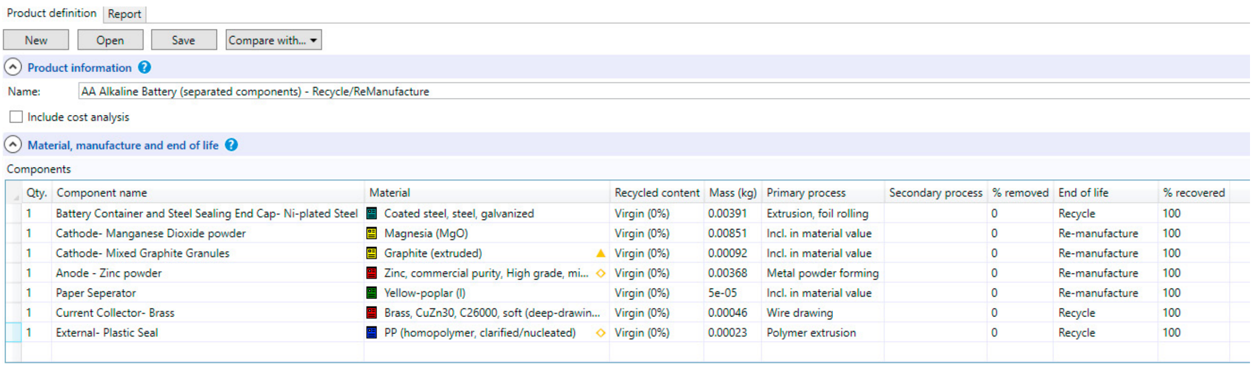

Fig. 5. Screen shot for AA Alkaline Battery eco audit in CES EduPack for segregated components. Shown with Recycle or Remanufacture EOL.

Figure 6 shows for the AA Battery separate components with Recycle/ReManufacture EOL. Energy (MJ) consumed (left) and carbon dioxide footprint (right) due to extracting the material, manufacturing, transporting, use, and disposal of AA alkaline battery. Energy saved and carbon dioxide emissions (kg) reduced at the end of the battery's life shown as end of life potential (per battery).

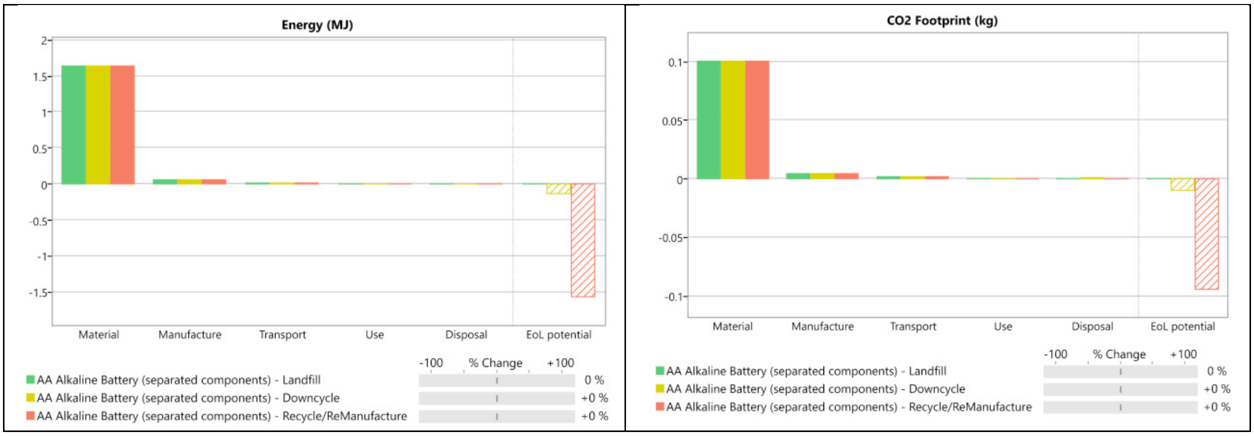

Fig. 6. AA Battery separate components with Recycle/ReManufacture EOL: Energy (MJ) consumed (left) and carbon dioxide footprint (right) due to extracting the material, manufacturing, transporting, use, and disposal of AA alkaline battery. Energy saved and carbon dioxide emissions (kg) saved at the end of the battery's life shown as end of life potential (per battery).

For AA Battery separate components with Recycle/ReManufacture EOL, Table 6 lists the values of the embodied material (MJ) values (does not include the contributions of transportation and use) energy and carbon dioxide emissions (kg) saved at the end of the battery's life shown as end of life potential (per battery).

Table 6. Values of the embodied material (MJ) values.

AA Battery- Alkaline	Landfill	Downcycle	Recycle (or Re-manufacture)
End of life potential Energy (MJ)	0	-0.274	-1.55
End of life potential CO_2 Footprint (Kg)	0	-.0197	-0.0939

For the Recycle/ReManufacture scenario, Table 7 lists the breakdown of the aggregate **Embodied Material energy** values are listed by component above in Table 6 which shows the largest % values are due to the cathode and anode powders. **CO2 footprint** similar supportive values are found for the Recycle/ReManufacture scenario but are not listed.

Table 7. Summary values by component: Embodied Material energy.

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass processed** (kg)	Energy (MJ)	%
Battery Container and Steel Sealing End Cap- Ni-plated Steel Can	Coated steel, steel, galvanized	Virgin (0%)	0.0039	1	0.0039	0.16	9.5
Cathode- Manganese Dioxide powder	Magnesia (MgO)	Virgin (0%)	0.0085	1	0.0085	1.1	65.3
Cathode- Mixed Graphite Granules	Graphite (extruded)	Virgin (0%)	0.00092	1	0.00092	0.2	12.3
Anode - Zinc powder	Zinc, commercial purity, High grade, min. 99.9%	Virgin (0%)	0.0037	1	0.0037	0.17	10.3
Paper separator	Yellow-poplar (l)	Virgin (0%)	5e-05	1	5e-05	0.00061	0.0
Current Collector- Brass	Brass, CuZn30, C26000, soft (deep-drawing/cartridge brass)	Virgin (0%)	0.00046	1	0.00046	0.025	1.5
External- Plastic Seal	PP (homopolymer, clarified/nucleated)	Virgin (0%)	0.00023	1	0.00023	0.016	1.0
Total				**7**	**0.018**	**1.6**	**100**

For the Recycle/ReManufacture scenario, the breakdown of the aggregate **EOL Potential Embodied Material energy** values are listed in Table 8.

Table 8. Summary values by component: EOL Potential Embodied Material energy savings

Component	End of life option	% recovered	Energy (MJ)	%
Battery Container and Steel Sealing End Cap- Ni-plated Steel Can	Recycle	100.0	-0.12	7.5
Cathode- Manganese Dioxide powder	Re-manufacture	100.0	-1	67.5
Cathode- Mixed Graphite Granules	Re-manufacture	100.0	-0.2	12.8
Anode - Zinc powder	Re-manufacture	100.0	-0.16	10.2
Paper separator	Re-manufacture	100.0	-0.00046	0.0
Current Collector- Brass	Recycle	100.0	-0.019	1.3
External- Plastic Seal	Recycle	100.0	-0.01	0.7
Total			**-1.6**	**100**

For the Recycle/ReManufacture scenario, the breakdown of the aggregate **EOL Potential CO2 footprint** values are listed in Table 9.

Table 9. Summary values by component: EOL Potential CO2 savings

Component	End of life option	% recovered	CO2 footprint (kg)	%
Battery Container and Steel Sealing End Cap- Ni-plated Steel Can	Recycle	100.0	-0.0087	9.3
Cathode- Manganese Dioxide powder	Re-manufacture	100.0	-0.056	59.8
Cathode- Mixed Graphite Granules	Re-manufacture	100.0	-0.015	16.0
Anode - Zinc powder	Re-manufacture	100.0	-0.013	13.4
Paper Separator	Re-manufacture	100.0	-2e-05	0.0
Current Collector- Brass	Recycle	100.0	-0.0012	1.3
External- Plastic Seal	Recycle	100.0	-0.00016	0.2
Total			**-0.094**	**100**

5. Conclusions

Alkaline batteries account for 80% of manufactured batteries in the US and over 10 billion individual batteries are produced worldwide annually most of which are disposed of in landfills [7]. Assuming that of these 8 billion alkaline batteries about half are size AA, the estimated number is 4 billion units annual. The LCA results for a unit battery (based on CES data under the Electrical components module (ECO audit only option)) estimate energy savings and CO2 footprint reduction of about 1 MJ and 0.072 kg, respectively, per each AA alkaline battery. Recycling the estimated annual production of 4 billion units would yield energy savings and CO2 footprint reduction of about (1 MJ x 4 x 10^{9} =) 4 x 10^{15} J and (0.072 kg x 4 x 10^{9} =) 2.88 x 10^{8} CO2 kg, respectively, annually. Repeating the analysis after segregating the battery components, the savings are even larger based on the EOL potential estimates of energy savings and CO2 footprint reduction of about (1.55 MJ x 4 x 10^{9} =) 6.2 x 10^{15} J and (0.0939 kg x 4 x 10^{9} =) 3.75 x 10^{8} CO2 kg, respectively. These findings suggest for recycle/remanufacture option is made technically feasible, huge savings in energy and CO2 can be realized.

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References

[1] Malavika, C. R. (2004, June 28). Environmental Effects Associated with Battery Disposal. http://www.frost.com/sublib/display-market-insight-top.do?id=20759887
[2] Battery University (2018) BU-705: How to Recycle Batteries. Accessed April 30, 2019 https://batteryuniversity.com/learn/article/recycling_batteries
[3] Battery University (2018) BU-301a: Types of Battery Cells. Accessed April 30, 2019 https://batteryuniversity.com/learn/article/types_of_battery_cells
[4] Haldemana, B., & Sigmund, W. (2018). Batteries for Home Electronics. Accessed April 30, 2019 http://www.myfloridahomeenergy.com/help/library/appliances-electronics/batteries-electronics/#sthash.jbSclDsf.dpbs
[5] Granta Design
[6] Duracell. (2016). Product Technical Data Sheets. Accessed April 17, 2019 https://docs-asia.electrocomponents.com/webdocs/0027/0900766b8002747e.pdf
[7] https://en.wikipedia.org/wiki/Alkaline_battery Accessed April 30, 2019