Single-Use Alkaline Battery Case Study

The Potential Impacts of Extended Producer Responsibility (EPR) in California on Global Greenhouse Gas (GHG) Emissions

California Department of Resources Recycling and Recovery

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Table of Contents

Background

This case study supports responsibilities of the Department of Resources Recycling and Recovery (CalRecycle, formerly known as the California Integrated Waste Management Board) under the California Air Resources Board Scoping Plan to address greenhouse gas emissions through an Extended Producer Responsibility (EPR) approach. Specifically, this case study assesses the extent to which product life-cycle greenhouse gas emissions might be reduced through possible product design, manufacturing, and end-of-life management strategies introduced under a producer's EPR initiatives.

EPR is a mandatory type of product stewardship that includes—at a minimum—that a producer's responsibility for its product extends to post-consumer management of that product and its packaging. In practical terms, this means that a producer (manufacturer, brand owner, or an organization that represents is interests) designs, manages, and implements a product stewardship and recycling program. While there is government oversight, the product stewardship and recycling program is financed and operated by the private sector. The goal is to provide incentives to producers to incorporate environmental considerations into the design of their products and packaging as they accrue the costs savings associated with design for recycling or end-of-life management.

The California Global Warming Solutions Act of 2006 (AB 32) requires greenhouse gas emissions to be reduced to 1990 levels by the year 2020. A primary aim of CalRecycle is to achieve high recycling rates and advance EPR to reduce emissions both in-state as well as within the connected global economy.

CalRecycle contracted with the University of California at Berkeley (UC Berkeley) and the University of California at Santa Barbara (UC Santa Barbara) with the objectives of developing several scientifically-based approaches to analyze life-cycle environmental impacts of products, preparing case studies for selected products, and providing California-specific guidelines for determining if and when a product purchased with recycled content has reduced associated greenhouse gas emissions as compared to a similar product made from virgin materials. In this report, the only environmental impacts considered are energy demand (in MJ net calorific value) and greenhouse gas emissions (in kg CO_2E). The greenhouse gas emission estimates use the 100-year global warming potential (GWP100) approach. Other environmental impacts, such as air quality, toxicity, and land/water use, are not considered in the report, although they may have significant implications.

This report contains the case study for single-use alkaline batteries, and was prepared by UC Berkeley and UC Santa Barbara under the aforementioned contracts. It uses life-cycle assessment (LCA) methodology to estimate the greenhouse gas emission reductions that could be achieved through product stewardship approaches. There are two major methods for performing life-cycle assessment: process-based LCA and economic input-output (EIO-LCA). Process-based LCA uses a model of the sequence of processes involved in a product's life cycle to estimate environmental impacts, which are computed by summing the impacts of all the processes. Process LCA tends to be more accurate for specific product systems but often omits significant upstream impacts due to lack of data. In contrast, EIO-LCA uses an economic input-output model of the entire economy which has been extended with estimates of sector-wide environmental exchanges (such as sector energy use and emissions). Using the EIO model avoids the truncation error inherent to process

LCA; however, it suffers from poor specificity and potentially poor accuracy for products that are not representative of their sector as a whole.

The only factors that determine environmental impact under an EIO-LCA model are economic sector and producer price, so comparisons between products within the same sector will depend strictly on their relative cost. Thus, economic sectors that vary widely in incurred environmental impacts per dollar value of product will tend to be more poorly modeled by the tool. Sectors with a relatively higher level of homogeneity in their included activities or produced outputs will be more aptly modeled (Hendrickson et al.2005). EIO-LCA also does not take into account the use or post-consumer phases of a product life-cycle.

A hybrid approach is intended to take advantage of the strengths of both methods (Suh and Huppes 2002). In this project, a hybrid approach is used by employing EIO-LCA methods to account for upstream or "supply chain" impacts of producing a given product (and for which sectoral averages are an appropriate proxy) and process-based LCA to account for the impacts of forward logistics (i.e., transport from manufacturer to retailer), use (if applicable), and end-of-life management (i.e., collection, disposal, and processing).

The specific EIO-LCA model used in this study is the multi-region input-output (MRIO) LCA model developed by UC Berkeley and Carnegie Mellon University (Masanet et al. 2012). It employs economic input-output modeling techniques to separate purchases and greenhouse gas emissions into three regions; California, the rest of the United States, and the rest of the world. The model is based on the single-region U.S. national EIO-LCA model developed by Carnegie Mellon University, which can be found at http://www.eiolca.net.

Documentation on this website may be beneficial to readers that are new to economic input-output modeling. Both models use the North American Industry Classification System (NAICS), for identifying the producing sector of a given product; NAICS codes are maintained by the U.S. Census Bureau. NAICS is the standard classification used by federal statistical agencies for the purpose of collecting, analyzing, and publishing statistical data related to the U.S. business economy. The MRIO model is based on the 2002 benchmark input-output model maintained by the U.S. Bureau of Economic Analysis (Stevens, 2007). Figure shows the relationship between the MRIO model and the process model used in the study series.

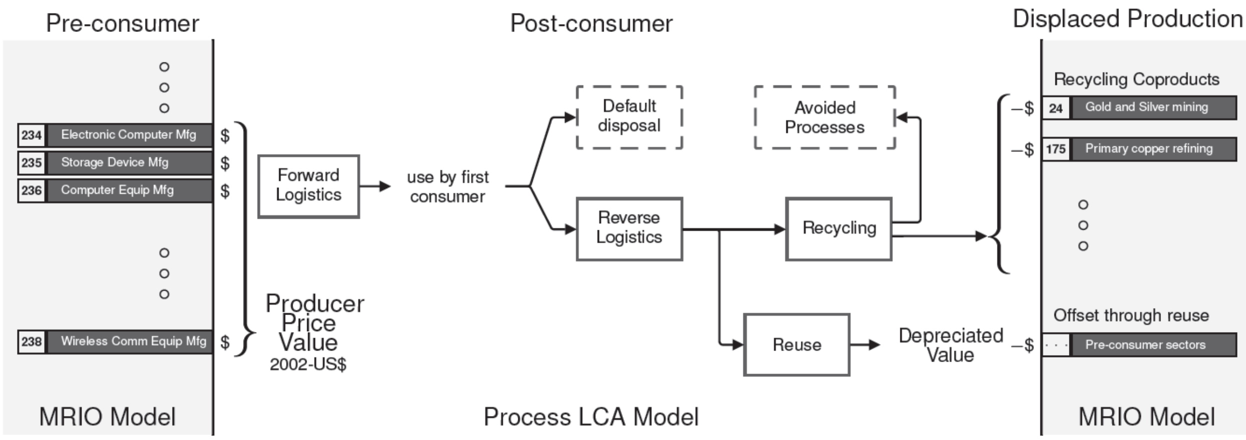


Figure 1: In the case studies, greenhouse gas emissions from product manufacturing and end-of-life management are calculated by combining MRIO-LCA with process-based LCA. The depiction shows a model of a desktop computer system as an example.

Process-based LCA is used to estimate the greenhouse gas emissions from forward and reverse logistics and product end-of-life management. Forward logistics refers to the shipment of products from the point of production to the point of consumption; reverse logistics indicates recovery of the products from consumers after the products' useful life. The process-based LCA model and approaches were developed by UC Santa Barbara in this case study series.

For each modeled process, the most appropriate process inventory data are chosen from a range of public and proprietary life-cycle inventory databases, including Ecoinvent, GaBi, and the U.S. life-cycle inventory (LCI) database. In some cases UC Santa Barbara complemented these data sources by primary data collection. Generally, processes involved in product end-of-life management are landfill, reverse logistics, reprocessing operations such as disassembly, recycling and refurbishment, and the production processes avoided by secondary outputs from reuse and recycling activities.

For example, the greenhouse gas emission reductions from materials recycling are calculated as the greenhouse gas savings from avoided landfill and avoided primary production reduced by the added greenhouse gas emissions from reverse logistics and reprocessing (

Figure **1**).

In the general life-cycle assessment methodology, this method is typically called the avoided burden approach or (consequential) system expansion. If it was unclear which exact process was avoided by the secondary resources, the MRIO-LCA model was used to assess displaced economic activity instead of avoided processes.

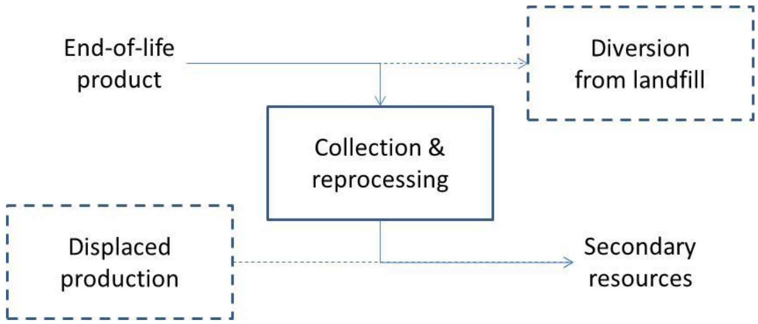


Figure 1: Analytical framework to assess greenhouse gas emissions reductions from end-of-life activities. Processes in dashed lines are avoided through collection and reprocessing of end-of-life products.

Product overview

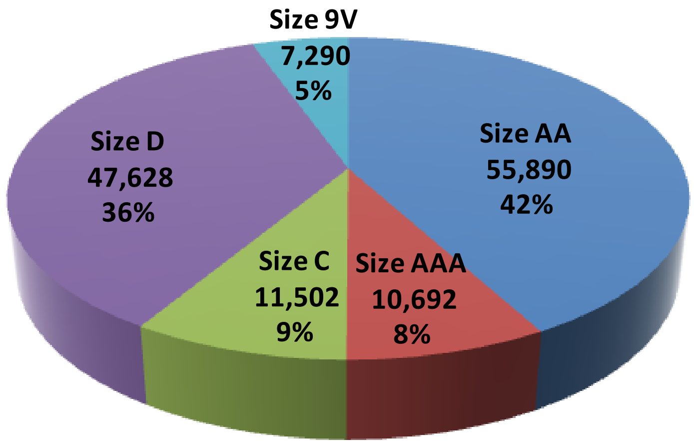
Single-use batteries are manufactured using several different chemistries, including alkaline manganese, carbon zinc, lithium manganese-dioxide, and silver dioxide (EPBA 2007). Of these, alkaline manganese batteries—hereafter referred to as "alkaline" batteries—are the most commonly purchased in the United States. Single-use battery shipments in the United States were estimated at 5.4 billion units in 2010, and 75 percent of these (around 4 billion) were alkaline batteries (Battery Summit 2011). Thus, we focus our case study on alkaline batteries given their predominance in the U.S. single-use battery market.

Table 1 summarizes published data on the mass of alkaline batteries by type, and the percentages of each type, that comprised total U.S. sales in 2007 (the latest year such data are available). Figure 3 presents the study team's estimates of the total U.S. mass shipments of each alkaline battery type in 2010, based on the 2007 sales data in Table 1 and assuming U.S. alkaline battery sales of 4 billion units. An estimated total of 133,000 metric tons (Mg) of alkaline batteries were shipped in the United States in 2010. Although size D batteries comprise less than 10 percent of estimated shipments, they represent the second largest mass flow (around 48,000 Mg) behind size AA batteries (around 56,000 Mg). Together, sizes AA and D accounted for nearly 80 percent of mass shipments.

Table 1: 2007 U.S. alkaline battery sales by size.

Size	% of 2007 sales	Weight of battery (g)
AA	60%	23
AAA	24%	11
C	4%	71
D	8%	147
9V	4%	45

Source: Battery Summit (2011)



Source: Derived from data in Battery Summit (2011)

Figure 3: Estimated 2010 U.S. mass shipments (Mg) of alkaline batteries by size.

Primary data on the annual purchases of alkaline batteries in California could not be found in the public domain. As a result, the study estimated in-state consumption by assuming that California's share of national battery shipments is proportional to its population. This approach was previously used by the California Integrated Waste Management Board (CIWMB 2002) to estimate that slightly over 500 million batteries (of all types and sizes) were sold in California in 2001. The 2010 population of California was 37,254,000, or around 12 percent of the U.S. total population (U.S. Census 2011a). Thus, we estimate that 490 million alkaline batteries were sold in California in 2010, which equates to 13 batteries per person and equates to roughly 16,000 Mg of alkaline batteries sales. Our estimates for California are summarized in Figure 4.

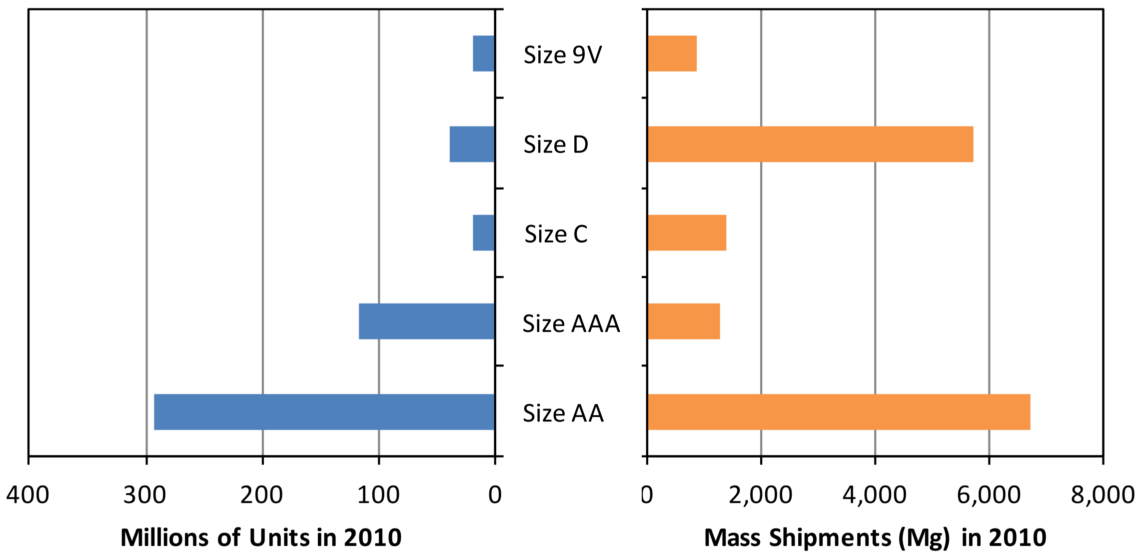


Figure 4: Estimated 2010 California sales of alkaline batteries.

Table 2 summarizes the total value of U.S. shipments, exports, and imports of single-use (i.e., primary) batteries of all chemistries in 2010. These estimates are based on U.S. economic survey data for the U.S. primary battery manufacturing sector, which falls under NAICS code 335912 (U.S. Census 2011b, 2011c). These data suggest that majority of single-use batteries purchased in the United States are domestically manufactured.

Five major manufacturers dominate the U.S. single-use battery market: Duracell, Energizer, Spectrum (Rayovac), Panasonic, and Kodak (Battery Summit 2011). Annual corporate reports and financial filings by these manufacturers (e.g., Spectrum Brands 2011; Energizer Holdings 2011) indicate that manufacturing plants are located around the United States (e.g., in Missouri, North Carolina, and Wisconsin), but also that no plants are located in California. No credible data could be found on the mass or types of batteries exported and imported.

Trade statistics from the U.S. Census Bureau indicate that the roughly 40 percent of primary battery imports (on an economic value basis) originate in China, followed by Japan (13 percent), Indonesia (8 percent), Israel (7 percent), and Germany (6 percent) (U.S. Census Bureau 2012a). However, U.S. trade data are only available at the commodity level (i.e., for all primary battery types), so it was not possible to estimate source countries by battery size or chemistry.

Table 2: Summary statistics of U.S. primary battery production and apparent consumption.

Description	Value ($ million) in 2010
Value of product shipments, U.S. production	4,600
Value of exports	787
Value of imports	572
Apparent consumption (shipments – exports + imports)	4,385
Imports as % of apparent consumption	13%

Figure 5 summarizes our estimates of 2010 mass flows of alkaline batteries in California. In the absence of import/export mass data, we used value of imports as a proxy for mass flows from imports. This approach resulted in an estimate of 13 percent of California's 2010 purchased alkaline batteries (2,100 Mg) coming from imports.

Data on end-of-life recycling were obtained from CalRecycle's Statewide Household Hazardous Waste Rates and Trends spreadsheet (CalRecycle 2012), which states than an estimated 2.6 million pounds of "other batteries, non-rechargeable" were collected in 2010. "Other batteries, non-rechargeable" are defined by CalRecycle as "any type of battery other than lead-acid (automotive) batteries. Examples include household batteries such as AA, AAA, D, button cell, and 9 volt … batteries used for flashlights, small appliances, watches, and hearing aids" (CalRecycle 2009). Based on the assumption that 75 percent of California primary battery sales are alkaline batteries, we estimate that 2 million pounds (or 907 metric tons) of alkaline batteries were collected for recycling in 2010. This amount represents only 6 percent of the estimated 2010 mass purchases of alkaline batteries, which suggests that the vast majority of batteries were either not yet used, discarded into the municipal solid waste system, or stored in the home after use (commonly referred to as "hoarding").

Credible and consistent data on post-purchase consumer behavior regarding battery storage and use, hoarding of spent batteries, and disposal channels for spent batteries are not available in the public domain. Indeed, in its 2009 *Municipal Hazardous or Special Waste Program Plan*, Stewardship Ontario states that "further study on hoarding assumptions, such as a scientifically valid household survey, need to occur in order to establish a valid hoarding rate" (Stewardship Ontario 2009). In the absence of credible data, Stewardship Ontario (2009) evaluates the implications of different hoarding periods (5 years and 15 years) on the availability of spent batteries for collection using a battery stock and flow model with an assumed average lifespan of three years for alkaline batteries (Stewardship Ontario 2009).

In this case study, we take a simplified approach to modeling the stocks and flows of California's alkaline batteries in 2010. We assume an average lifespan of three years, followed by a hoarding period of eight years based on data in Stewardship Ontario (2009). These assumptions result in an eight-year residence period in California homes, which we refer to as "installed stock," which is estimated at 128,000 Mg. Notable in Figure 5 is that the 2010 mass of EOL batteries collected for recycling (900 Mg) is much smaller than the total estimated discards (16,000 Mg) based on an eight-year residence period. This discrepancy suggests that California consumers may have increased hoarding in light of the state's recent battery disposal ban or may be continuing to discard batteries as municipal solid waste. In the absence of household survey data, the study team has labeled the 15,100 Mg of unaccounted for mass flows as "unknown."

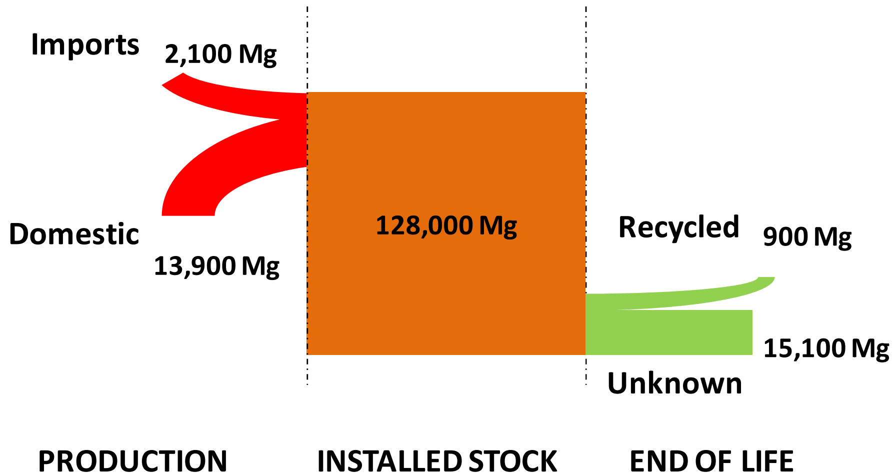


Figure 5: Estimated 2010 mass flows from California sales of single-use batteries.

Emissions from production

To estimate the greenhouse gas emissions associated with producing the estimated 16,000 Mg of alkaline batteries purchased by Californians in 2010, the study team first estimated the 2010 producer price of batteries from the data in Table 2. The producer price represents the net selling value of all products shipped from the producing sector prior to any price markups that occur for shipping, insurance, wholesale, or retail operations prior to purchase by the consumer.

Considering the estimated 5.4 billion units of single use batteries purchased in the United States in 2010 (Battery Summit 2011), and the estimated 2010 producer value of $4.39 billion for total U.S. apparent consumption in Table 2, the study team arrived a 2010 producer price estimate of $0.81 per unit. This value translates to a total producer value of $399 million for the estimated 490 million alkaline batteries purchased by Californians in 2010.

A conversion to 2002 producer price is necessary for compatibility with the MRIO model, which uses the 2002 U.S. input-output accounts as its basis (Masanet et al. 2012). The study team used a 2002:2010 producer price index (PPI) ratio of 100:138 for primary battery manufacture (U.S. BLS 2011). The PPI provides a means of converting producer prices between different years taking inflation into account. Using this PPI ratio, we estimated that the producer value of 2010 alkaline battery purchases by Californians amounted to $288 million in 2002 producer prices.

The MRIO model estimates that the greenhouse gas emissions associated with $288 million of output from the primary batteries sector (335912) amounts to roughly 144,000 Mg of carbon dioxide equivalents (CO_2E). On a mass basis, this amount converts to 9 kg CO_2E per kg of primary battery produced for use in California.

Figure 6 summarizes greenhouse gas emissions estimates for the top 10 input-output sectors in the production chain for primary batteries, on a per dollar of production basis. The top emitter is the iron and steel sector, which might be attributable to steel's role as the largest mass fraction material in a typical alkaline battery (Olivetti et al. 2011). Battery manufacture itself is the second largest emitter, followed by nonferrous metals production (e.g., zinc for the battery's anode). The largest sources of emissions are coal use and process CO_2E in steelmaking, electricity use in primary battery manufacture, natural gas use in all metals sectors, and petroleum for supply chain truck transportation.

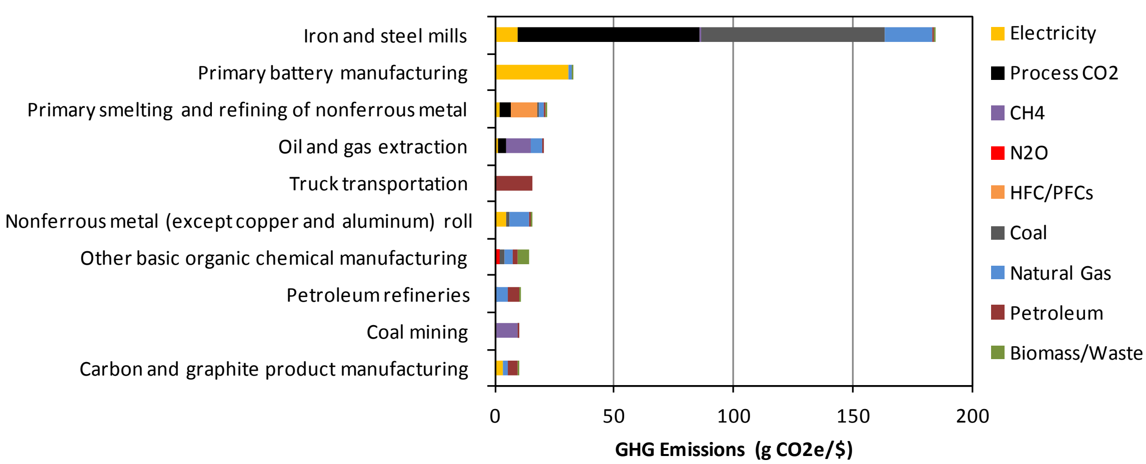


Figure 6: Top 10 sectors for greenhouse gas emissions in the primary battery production chain.

Emissions from forward logistics

Forward logistics refers to the transportation of finished batteries from the manufacturer to wholesale and/or retail outlets for purchase by the final consumer. Emissions from forward logistics were estimated in four steps.

First, the typical energy and greenhouse gas emissions intensities of various U.S. freight modes were established from the U.S. LCI database (NREL 2011). These intensities are summarized in Table 3.

Table 3: Energy and greenhouse gas emissions intensities for common freight modes.

Mode	Energy (MJ/t-km)	CO2 (kg/t-km)
Transport, barge, diesel powered	3.49E-01	2.81E-02
Transport, combination truck, diesel powered	9.90E-01	7.99E-02
Transport, ocean freighter, residual fuel oil powered	2.06E-01	1.60E-02
Transport, train, diesel powered	2.36E-01	1.89E-02

Source: NREL (2011)

Second, the typical modes of domestic freight transport for batteries were estimated based on the U.S. Bureau of Transportation Statistics' Commodity Flow Survey data for shipments from the electrical equipment industry (U.S. Census Bureau 2004).

The data from this survey suggest that of reported ton-miles for single-mode freight (25.2 billion), the vast majority of ton-miles (23.9 billion) were by truck, with most of the remainder of ton-miles by rail (0.5 billion).

Third, the average shipment distances occurring domestically and from imports were estimated based on regional economic data and online distance mapping software (Google Maps and PortWorld). For domestically produced batteries, data from the U.S. Census Bureau suggest that roughly 40 percent of U.S. employment in the primary battery sector is located in North Carolina, followed by New York (30 percent), and Georgia (13 percent) (U.S. Census Bureau 2012b). Using an employment-weighted average of driving distances from the center of each state to the center of California produced an estimated domestic shipping distance of 4,200 km.

Trade statistics from the U.S. Census Bureau indicate that the roughly 40 percent of primary battery imports (on an economic value basis) originate in China, followed by Japan (13 percent), Indonesia (8 percent), Israel (7 percent), and Germany (6 percent) (U.S. Census Bureau 2012a). Based on these data, the value-weighted average shipping distances for imports to the United States were estimated at 12,000 km (to western ports from China, Japan, and Indonesia) and 8,400 km (to eastern ports from Israel and Germany). An additional 4,500 km of domestic shipping by truck was assumed for transportation of imports from eastern ports to California.

Fourth, using the estimated shipping distances, modes, and purchased mass of alkaline batteries, the greenhouse gas emissions for forward logistics were estimated and summarized in Table 4. The total estimated greenhouse gas emissions of forward logistics for California-purchased alkaline batteries in 2010 is estimated at 5,260 Mg CO_2E, an amount equivalent to roughly 4 percent of the production emissions associated with purchased batteries (144,000 Mg CO_2E). Thus, while not insignificant, the emissions of forward logistics likely represent only a small fraction of the cradle-to-consumer system for alkaline batteries.

Table 4: Estimated 2010 emissions from forward logistics.

Transport activity	Mode	Distance (km)	Mass (Mg)	GHG emissions (Mg CO_2E)
Domestic shipments of domestically-produced batteries	Diesel combination truck	4,200	13,900	4,665
Ocean shipments of foreign-produced batteries to Western U.S. ports	Residual fuel ocean freighter	12,000	1,465	281
Ocean shipments of foreign-produced batteries to Eastern U.S. ports	Residual fuel ocean freighter	8,400	635	85
Domestic shipments of foreign-produced batteries from Eastern U.S. ports	Diesel combination truck	4,500	635	228
Total				**5,260**

Emissions from end-of-life operations

The UC Berkeley team adopted the UC Santa Barbara end-of-life (EOL) processed-based model for estimating the greenhouse gas emissions associated with different end-of-life pathways for spent alkaline batteries in California. To estimate the mass composition of spent alkaline batteries, we relied on publicly-available data from Olivetti et al. (2011), which are summarized in Table 5. While spent batteries contain multiple materials, only steel, manganese, and zinc are recovered in current recycling processes (Battery Summit 2011). Moreover, recoverable grades of the latter two materials depend on the recycling technology.

Table 5: Estimated material composition of spent alkaline batteries.

Material	Mass (g) per 1 kg batteries
Manganese	250
Zinc	190*
Steel	190
Potassium	26
Graphite	36
Copper	20
Nickel	4
PVC	15
Nylon	15
Paper	15
Moisture content ~6% by mass	

* This number combines the zinc from the electrode, brass, and galvanized steel

Source: Olivetti et al. (2012)

Figure 7 shows how the various end-of-life pathways compare on a per-kg basis, which are based on detailed process-level end-of-life analyses by Olivetti et al. (2011) (which were based on California assumptions) and available options in the UC Santa Barbara end-of-life model. The study team considered four recycling collection pathways, in addition to the landfill pathway. The landfill pathway was included as a means of estimating end-of-life emissions in the case of illegal disposal. The pathways considered were:

- Landfill;
- End-of-life curbside pickup of spent batteries for recycling;
- Consumer drop-off of spent batteries for recycling to a retail store;
- Consumer drop-off of spent batteries for recycling at a central municipal location; and
- Consumer mail-in of spent batteries via the U.S. Postal Service for recycling.

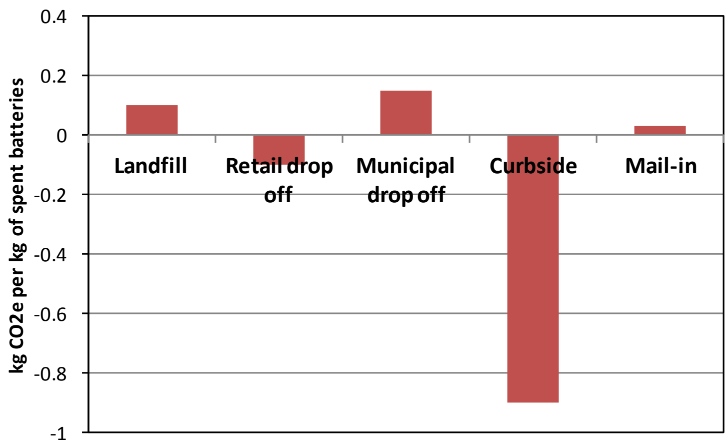


Figure 7: Per-kg comparisons of different end-of-life pathways for spent alkaline batteries.

The differences between the different pathways for recycling are mainly due to the transport distances and emissions intensities of the transport modes associated with the collection scheme in each pathway. For example, curbside collection is based on existing truck systems for waste, which generally operate at high capacity factors, which results in lower emissions per ton-km of battery transport than the private vehicles used for retail and municipal drop-off.

Figure 8 plots two cases for the 2010 end-of-life greenhouse gas emissions associated with spent alkaline batteries in California. The first case assumes that the “unknown” mass flows in Figure 5 are hoarded, meaning that the average residence time in California homes is roughly 16 years (as opposed to the current assumption of eight years).

The recycled mass (900 Mg) is subject to the following assumptions based on a review of available drop-off locations for spent batteries in California (CalRecycle 2012): 80 percent via retail drop off and 20 percent via municipal drop off. These fractions should be refined and/or verified when improved data on actual drop off behavior in California emerge in the public domain. The second case assumes that the “unknown” mass flows in Figure 5 are disposed of illegally via landfill as a worst-case assumption. The difference between these cases underscores the criticality of spent battery recycling from a life-cycle greenhouse gas emissions perspective.

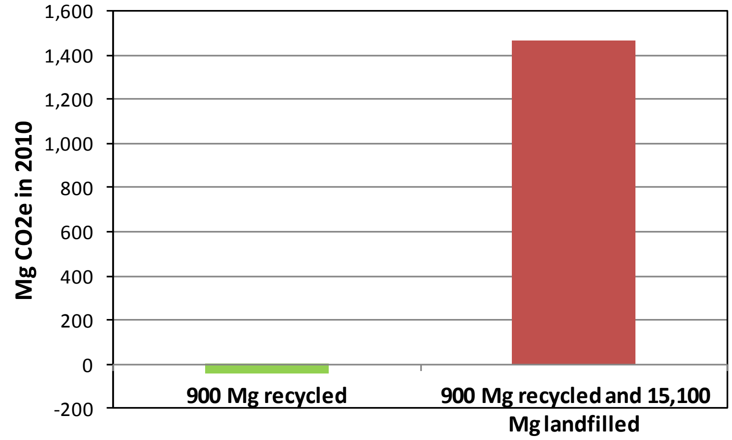


Figure 8: Estimated total greenhouse gas emissions associated with end-of-life recycling and disposal.

Opportunities for life-cycle emissions reductions

The study team conducted a global literature review to identify possible strategies for reducing the life-cycle impacts of primary batteries. As discussed above, the vast majority of greenhouse gas emissions attributable to the primary battery life-cycle are associated with its production phase. Identified recommendations for reducing the life-cycle greenhouse gas emissions therefore centered on improved recycling infrastructures, improved design, and improved supply chain management (Olivetti et al. 2011; Panasonic 2011). Specifically, we identified the following strategies:

- Design: reduce the mass of steel in the battery casing;
- Design: improve the useful life of the battery to extend product lifespan;
- Manufacturing: supply chain environmental management to reduce upstream impacts; and
- Recycling: improved recycling rates; maximum recycling technology.

Reduced steel mass in battery casing

Olivetti et al. (2011) suggest that reducing the thickness of the steel in the battery casing might be a fruitful option for reducing the life-cycle impacts of alkaline batteries, given the significant contribution of steel use the battery's environmental footprint. No data could be found in the public domain for achievable reductions in steel use for the battery casing. In practice, any reduction in steel use would have to be based on rigorous engineering design to ensure battery performance and reliability were not compromised, and that manufacturing quality and costs were acceptable for the improved design. The study team also adopted the assumption that, since batteries are a high-volume, global commodity product, most steel use reduction opportunities have already been realized due to reasons of cost and competitiveness among the world's major battery manufacturers. In light of these assumptions, the study team assumed that an additional 5 percent reduction in steel mass might be achievable, with the primary goal of illustrating the potential life-cycle greenhouse gas emissions reductions associated with this opportunity.

To model the effect of steel use reductions, the study team adjusted downward the required steel purchases for primary battery manufacture by 5 percent in the MRIO model.

Extended battery lifetime

Battery lifetime extension has long been a goal of the industry, due primarily to reasons of competitiveness and technological advantage in a competitive global marketplace. Still, advanced battery designs and chemistries continue to appear in the marketplace which hold promise for extending the lifetime of the average alkaline battery. Lifetime extension is a proven strategy for reducing the environmental footprints of many products, since the net result is that, over time, the consumer need not purchase as many product units to provide the same service (e.g., fewer batteries will be required over a given period to meet the same power needs).

The study team searched for the best-in-class battery technology to approximate the achievable lifetime extension in the installed stock of California alkaline batteries. We assumed that the best-in-class long-life battery could last as much as 30 percent longer than standard alkaline batteries, based on data in GNT (2008). These results are achieved through design improvements including more internal space, improved seals, and improved battery materials (i.e., the use of manganese dioxide and oxy-hydroxide titanium).

To approximate the effect of extended battery lifetime, the study team reduced annual purchases of new batteries by an amount commensurate with the battery lifetime extension. For example, for a lifetime extension of 30 percent, the annual purchases of new alkaline batteries (assuming 100 percent market penetration) would be reduced by a factor of 1/1.3.

Maximum supply chain efficiency

To estimate manufacturing and supply chain energy efficiency improvement potentials, this study utilized the eSTEP modeling methodology that is summarized in Masanet et al. (2009a, 2009b). The model currently includes best practice technology energy savings data for a range of energy efficiency measures in different input-output (IO) sectors, and for different energy end uses. It also contains key measures for non-energy-related greenhouse gas emissions in several IO sectors. A summary of the broad IO sectors, fuels, and non-energy greenhouse gas emissions covered by best practice technology data in the eSTEP model is provided in Masanet et al. (2012).

The eSTEP model was used to generate potential reductions in fuel use and emissions for all manufacturing, commercial, agricultural, mining, and water treatment sectors in the MRIO model as a means of approximating the potential supply chain emissions reductions a final manufacturer might drive throughout its supply chain by sourcing its inputs only from "low carbon" supply chain partners. As such, it provides an upper bound estimate on best practice supply chain emissions savings, since it assumes that best practices will be adopted at all sectors in its supply chain, whether those sectors are primary or very distant suppliers.

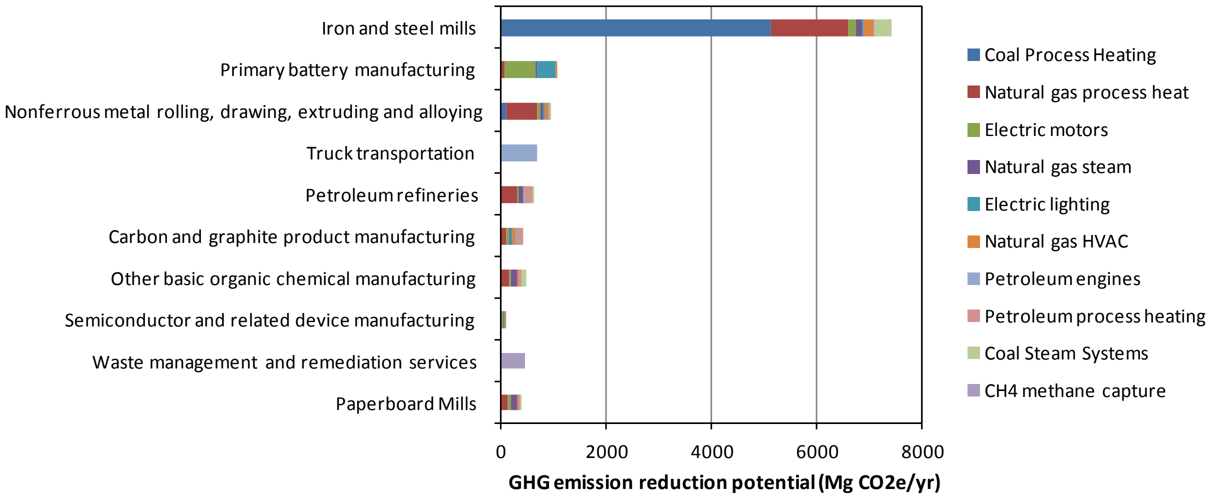


Figure 9: Supply chain greenhouse gas emissions reduction opportunities by sector and source.

Detailed results on the estimated supply chain improvement potentials for the manufacture of $288 million in primary batteries (i.e., California's 2010 demand) are presented in Figure 9. The results show the top 10 emissions reduction opportunities across the supply chain in terms of estimated emissions saved by fuel and emissions reduction opportunity area (for energy efficiency) and by greenhouse gas emissions type and abatement opportunity (for greenhouse gas emissions abatement measures).

Maximum EOL recycling

Lastly, for improved recycling we assessed a 100 percent recycling rate of all end-of-life batteries under the following assumptions for maximum end-of-life greenhouse gas emissions benefits:

- A hoarding period of five years, with all end-of-life batteries sent to recycling after their estimated residence time (lifespan plus hoarding period);
- A 30 percent battery lifetime extension to reflect the improvements considered earlier for improved battery materials; and
- Curbside pickup to minimize the greenhouse gas emissions intensity of collection

Figure 10 and Table 6 summarize the estimated life-cycle greenhouse gas emissions associated with the opportunities described above under two cases compared to the 2010 base case (i.e., the current estimates of life-cycle greenhouse gas emissions). The first case (partial savings) considers more modest improvements in each opportunity area as coarse way of acknowledging potential technical, market, and economic barriers that might prevent realization of the full technical potential for greenhouse gas emissions reductions. For example, although it is theoretically possible for all batteries purchased in California to be of the extended lifetime variety, due to issues of consumer preference or awareness the penetration of extended lifetime batteries may never reach 100 percent.

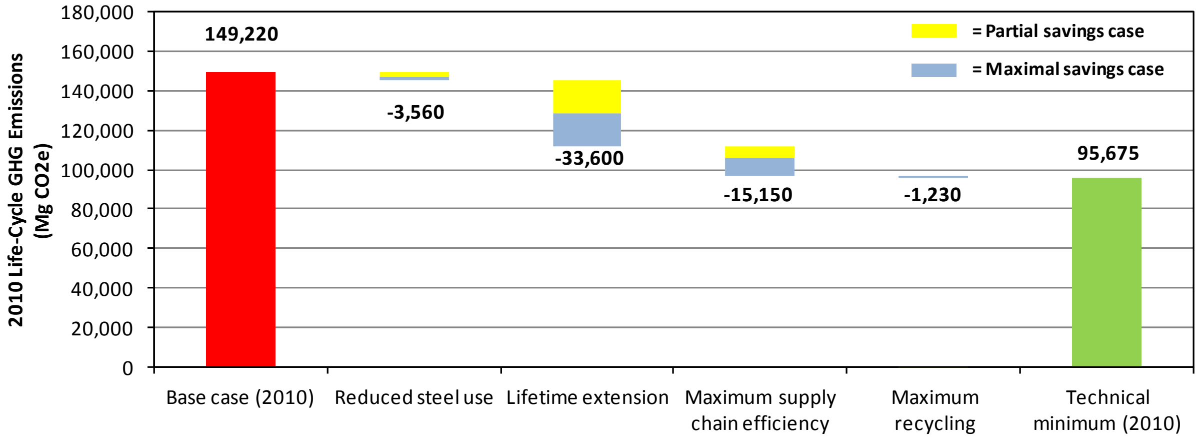


Figure 10: Estimated life-cycle greenhouse gas emissions reduction opportunities.

The second case (maximum savings) is based on the total estimated technical potential of the opportunity, and therefore represents an upper bound, best-case estimate for potential greenhouse gas emissions reductions. Note that all savings estimates within each case are additive, given that the opportunities were applied in cascading fashion to avoid double-counting. Furthermore, subsequent opportunities within a case took into account relevant mass and product changes associated with previous opportunities within that case. For example, the mass of end-of-life batteries available for recycling takes into account the reduced mass purchases of new batteries associated with lifetime extension. Lastly, the savings estimates in the maximal savings case are inclusive of, not additive to, the savings in the partial savings case.

Table 6: Summary of analysis assumptions for life-cycle improvement opportunities.

Opportunity area	Analysis details	Analysis case		
		Base case	Partial savings	Maximum savings
Reduced steel mass in casing	Key assumption(s)	Existing battery materials quantities (Table 5)	Steel mass in casing reduced by 2.5%	Steel mass in casing reduced by 5%
	GHG emissions savings compared to base case (Mg/yr)	--	1,190	3,560
Extended lifetime	Key assumption(s)	--	Battery lifetime extended by 15%	Battery lifetime extended by 30%
	GHG emissions savings compared to base case (Mg/yr)	--	16,900	33,600
Increased	Key	Current U.S.	50% of supply chain	100% of supply

supply chain efficiency	assumption(s)	average supply chain efficiency	efficiency potential is realized	chain efficiency potential is realized
	GHG emissions savings compared to base case (Mg/yr)	--	8,700	15,150
Increased EOL recycling	Key assumption(s)	900 Mg recycled; 80% via retail drop off and 20% via municipal drop off	8,000 Mg (50%) of spent batteries recycled via retail drop off	16,000 (100%) of spent batteries recycled via retail drop off
	GHG emissions savings compared to base case (Mg/yr)	--	1,350	1,230
All opportunities combined	GHG emissions savings compared to base case (Mg/yr)	--	28,140	53,540

Clearly, the largest opportunity lies in extending the useful life of single-use batteries, which has the effect of reducing overall annual purchases of batteries in California. The next largest opportunity is minimizing supply chain greenhouse gas emissions through best practice supply chain efficiency, which serves to reduce the overall "embodied" greenhouse gas emissions in the product. Figure 9 suggests that the greatest supply chain savings are to be had for purchased steel and nonferrous metals, and for improved process heating efficiency in each of these sectors. Primary battery manufacturers might also increase their own efficiency through improvements to electric motors and process heating systems.

Figures 10 and 11 plot the results for the 2010 base case and the 2010 technical minimum case (i.e., the base case minus the maximal savings case) by region of emissions as estimated by the MRIO model. Results are presented for California, the rest of the United States, and the rest of the world, as discussed in the background section.

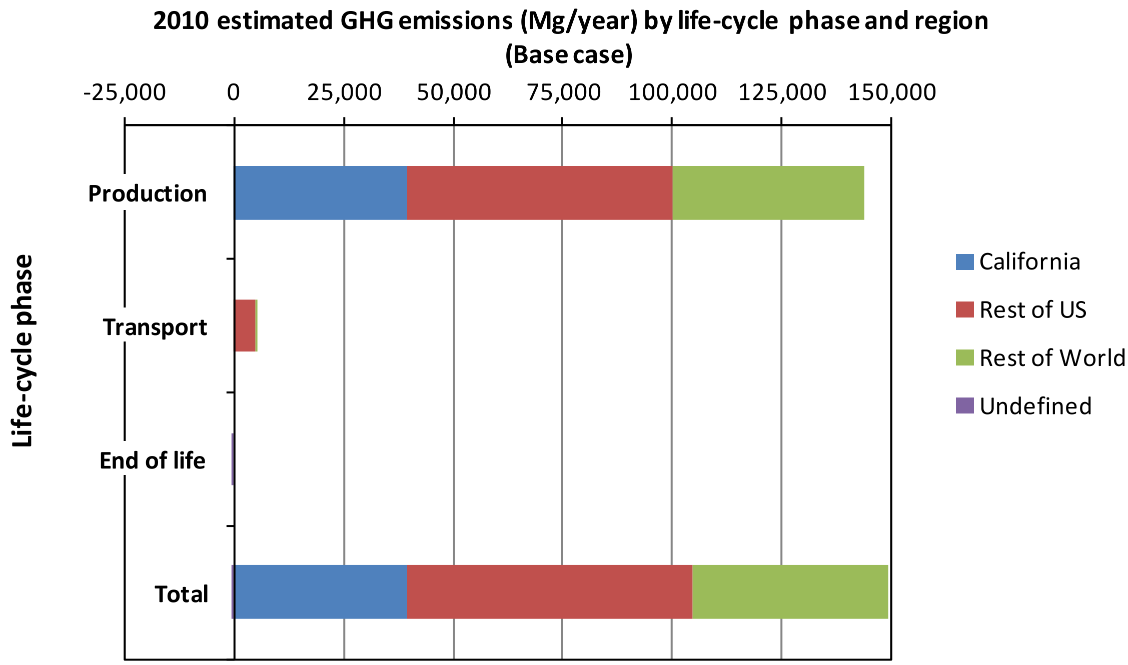


Figure 10: Regional breakdown of greenhouse gas emissions for the base case.

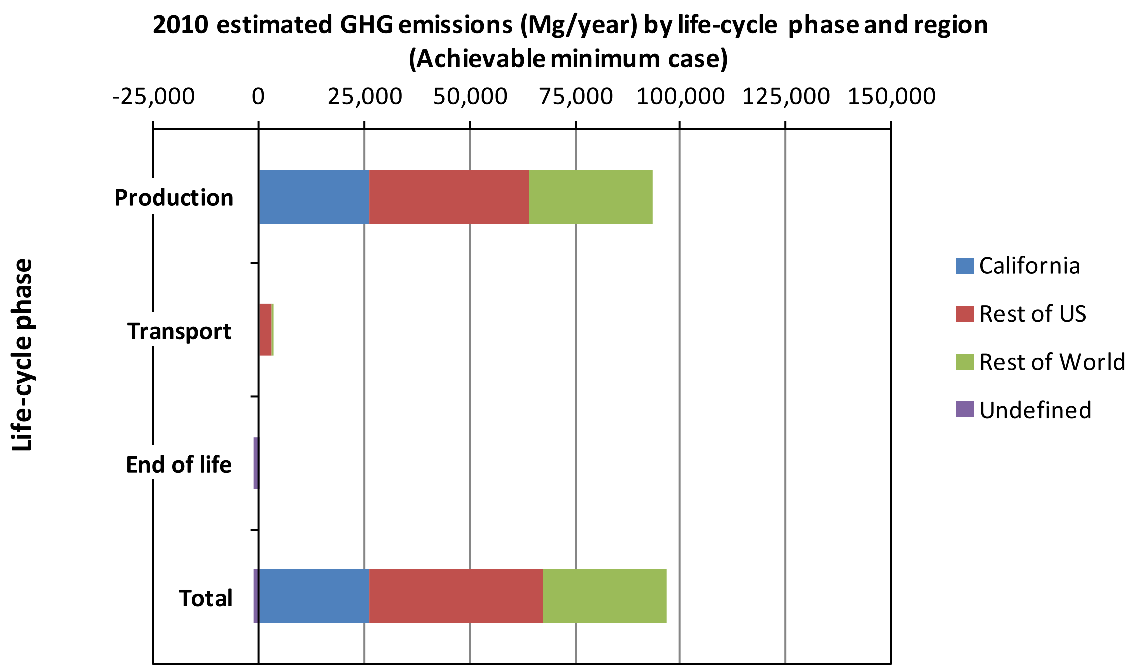


Figure 11: Regional breakdown of greenhouse gas emissions for the achievable minimum case.

Labor implications of increased recycling

A recent report by the Tellus Institute and Sound Resource Management (2011) attempted to estimate the job requirements of collection, recycling, and disposal systems for various components of municipal solid waste in the United States. The findings are reported in terms of jobs per 1,000 short tons (907 Mg) of material handled by collection, processing, manufacturing, and reuse/remanufacturing operations (for diverted waste) and by collection, landfill, and incineration (for disposed waste). While such estimates oversimplify the complex macroeconomic equilibrium analyses required to understand the job impacts of substituting materials and processes in an extended economic system, they can serve as a plausible estimate of potential job creation due to increased battery recycling for the purposes of this study. The job creation estimates are summarized in Table 7.

Table 7: Summary of job requirements for metals waste processing.

Material	Diverted Waste		
	Collection	Processing	Manufacturing
	Jobs per 1,000 tons		
Ferrous metals	1.67	2.00	4.12
Nonferrous metals	1.67	2.00	17.63

Source: Tellus et al. (2011)

In the maximum savings case, the recycling rate was increased to raise the mass processed for recycling from 900 Mg/yr to 12,300 Mg/yr (note that the maximum savings case also reduced end-of-life mass generated by extending product life through improved battery chemistry). Assuming that all reclaimed materials from California's end-of-life batteries would offset virgin materials use in new products, the estimated job impacts associated with the increased recycling in the maximum savings case (around 135 jobs added) are summarized in Table 8.

Table 8: Estimated job impacts associated with increased EOL battery recycling.

e	Unit	Diverted Waste (ferrous)			Diverted waste (nonferrous)		
		Collection	Processing	Manufacturing	Collection	Processing	Manufacturing
Base case	Mass (Mg)	170	170	170	400	400	400
	Jobs	0.3	0.4	0.8	0.7	0.9	7.8
Maximum savings	Mass (Mg)	2300	2300	2300	5400	5400	5400
	Jobs	4.2	5.1	10.4	9.9	11.9	105.0
Net change	Mass (Mg)	2130	2130	2130	5000	5000	5000
	Jobs	3.9	4.7	9.7	9.2	11.0	97.2

Conclusions

This case study estimated the life-cycle greenhouse gas emissions associated with the production, transport, and disposal of single-use alkaline batteries consumed by Californians and the potential for reducing these emissions through improvements to product design, manufacturing, and end-of-life management. The considered improvements might reduce the annual greenhouse gas emissions “footprint” of alkaline batteries in California by up to 36 percent through product lifetime extension, reduced steel content, increased end-of-life recycling, and improved manufacturing energy and emissions efficiencies. Battery sizes D and AA represent the most attractive targets for such improvements, given their predominance in terms of mass flows in California (see Figure 4).

Each of the considered improvements is relevant to EPR programs, although the exact mechanism for inducing each improvement will vary by EPR program design and the stakeholders in charge of EPR compliance. For example, an EPR program designed to minimize waste might provide producers with financial incentive to offer longer-lasting batteries, while an EPR program designed to reward “green” design and manufacturing features might provide motivation for improved manufacturing and supply chain energy and emissions efficiencies.

Regardless of the EPR program type, this case study has provided valuable quantitative estimates for scoping the potential emissions savings related to reduced impact batteries, which can provide guidance to policy makers and manufacturers on the most fruitful areas of improvement under various EPR initiatives. The maximum savings case results suggest that product lifetime extension and manufacturing efficiencies might lead to the most significant life-cycle greenhouse gas emissions reductions, while improved recycling and reduced steel use can lead to additional savings. The preliminary results for net job creation also suggest that improved recycling can have positive benefits on employment both inside and outside California.

In summary, batteries represent a reasonable opportunity for EPR programs due to the ready availability of environmental improvements through design, manufacture, and end-of-life strategies, which may offer California additional greenhouse gas emissions reductions beyond those expected under its current batteries recycling scheme.

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