# ROLE OF RECYCLING IN THE LIFE CYCLE OF BATTERIES

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## Abstract

Over the last few decades, rechargeable battery production has increased substantially. Applications including phones, computers, power tools, power storage, and electric-drive vehicles are either commonplace or will be in the next decade or so. Because advanced rechargeable batteries, like those using nickel metal hydride or lithium-ion chemistries, consist of less-plentiful and comparatively expensive materials (e.g., nickel, cobalt, cadmium, mischmetal) that often require considerable energy to be formed into battery components, battery recycling has the potential to significantly reduce the burdens associated with the life cycle of batteries. Therefore, the key issue is to determine the most practical type of recycling. Is it feasible to recover such components as anodes, cathodes, and electrolytes, or should the elements be recovered? Estimates of the impacts of battery recycling are given.

## Introduction

Concern over U.S. dependence on foreign oil and overall greenhouse gas emissions has spurred renewed interest in improving the nation's energy efficiency. To address these concerns, a number of initiatives and policies have been proposed, such as the Renewable Portfolio Standards enacted by many states to increase the share electricity generated from renewable sources. As another example, the U.S. government and the auto industry are promoting the development of affordable, advanced battery technologies for vehicle traction. The advantages of such batteries when used in electric-drive vehicles are reduced oil consumption and carbon dioxide emissions. These batteries could benefit the grid by providing load leveling via overnight charging or peak shaving via V2G (vehicle-to-grid) and, when no longer usable in vehicles, stationary storage for energy generated during off-peak periods. However, these advanced battery technologies are a significant departure in material composition from the lead acid batteries found in conventional vehicles. That raises the following question: What level of environmental benefit can these batteries potentially provide?

In the last few decades, the use of rechargeable batteries has increased significantly. To date, this increase has been driven mostly by the consumer electronic marketplace for such applications as cell phones, laptop computers, power tools, toys, remote sensing devices, and more recently hybrid electric vehicles. The type of rechargeable batteries employed for many of these applications was initially nickel cadmium, which has been replaced primarily by nickel metal hydride, which, in turn, is now being displaced by lithium-ion. Because of the value of some constituent elements in these batteries, considerable effort has been devoted to recycling them. However, less-valuable components are often discarded or sent to lower-value uses (downcycled).

While significant advances are being made in the recycling of rechargeable batteries, the environmental performance of those processes has not been quantified adequately, and the intended purpose of the output product (i.e., for batteries or other applications) has not been clear. For example, from an environmental performance point of view, is it better to recycle advanced battery materials (nickel, cobalt, lithium, misch metal) back into new batteries or use them for other products, like stainless steels? Further, the environmental performance of advanced battery manufacturing when using virgin materials needs to be further elucidated, which is the logical basis of a comparison for battery recycling.

The preferred approach to environmental evaluations of product systems is life cycle analysis (LCA) [ISO 14040, 14041, 14042]. LCA is a method that provides a system-wide perspective of a product or

service, one that considers all stages of its life cycle, including material production, system manufacture and assembly, service provision, maintenance and repair, and end-of-life processes. Our focus is on the quantitative component of LCA — that is, life cycle inventory analysis (LCI). Although, generally, the objective of a life cycle analysis is a cradle-to-grave evaluation, the focus in this study is on cradle-to-gate assessments. More specifically, our analysis sums the energy burdens associated with all processes used in the production of batteries and their constituent materials up to the point of a purchase-ready product. We do not consider product use. Rather than an end-of-life activity, recycling is instead considered to be a beginning-of-life process, which provides alternative resources for new batteries.

The purpose of this document is to review the status of advanced battery recycling and to estimate its environmental benefits. Existing battery recycling technologies are discussed, with an emphasis on identifying those approaches that are likely to offer the best environmental and cost performance. Environmental performance will be examined by using life cycle assessment, with a focus on energy and greenhouse gas emissions from cradle to gate, including battery manufacturing and the production of materials that make up batteries. The battery technologies considered are lead acid, nickel metal hydride, and the lithium-ion battery systems.

## Approaches

A number of approaches are either in current practice or being researched for recycling batteries and retrieving valuable materials. These include pyrometallurgical, chemical, and physical processes. The second one, the chemical approach, includes hydrometallurgical and solvent extraction processes. A depiction of battery recycling is shown in Figure 1. From an energy and resource consumption and process emissions point of view, the most desirable battery recycling scheme probably returns recycled battery materials to the production chain as close to battery production as possible. More specifically, returning battery metals to the elemental state is thought to be the least-desirable approach, whereas capturing battery cathodes and anodes for use in new batteries is the most attractive. However, if the recycling process itself has significant impacts, or the product is not usable because of obsolete composition or insufficient purity, recycling to building blocks could be preferred.

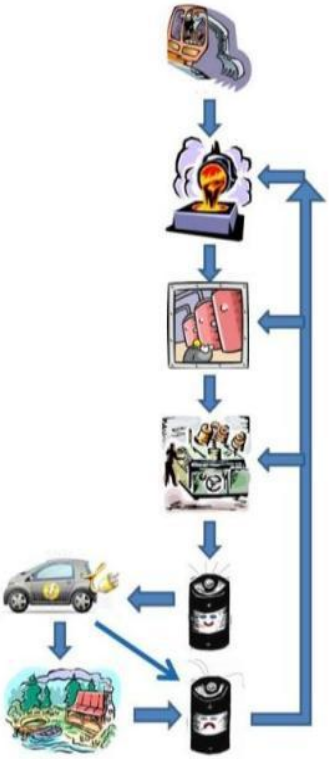

FIGURE 1. Depiction of Battery Recycling

**Pyrometallurgical recycling processes:** These are high-temperature processes, where batteries may or may not be broken up before being fed into a smelting furnace, from which metals are recovered. In this approach, materials are recovered as elements and subsequently reacted to make battery materials. Umicore, an advanced materials company, has major operations devoted to recycling nickel metal hydride, nickel cadmium, and lithium-ion batteries in this way (Figure 2). Umicore's primary interest is to recover nickel (Ni) and cobalt (Co), the latter of which currently commands high returns in the secondary marketplace. Although Umicore does not recover the lithium (Li) derived from Li-ion batteries at present, the company could in the future if prices justify it. If there is a reduction of cobalt use in Li-ion batteries, the concomitant lower yields of Co in the recycling stream could make Umicore's processes uneconomical. The materials recovered from the Umicore recycling system [Tytgat, 2009] are copper (Cu), iron (Fe), zinc (Zn), nickel hydroxide [$Ni(OH)_2$], and cobalt chloride ($CoCl_2$). The $CoCl_2$ is sent on to another operation and reacted with new lithium to produce lithium cobalt oxide ($LiCoO_2$) for use in new batteries. Umicore claims that using recycled Co reduces the production energy for $LiCoO_2$ by 70%, which would be a tremendous improvement. After breaking up lead acid batteries, RSR Corporation's smelting facility in Middletown, NY, recovers lead.

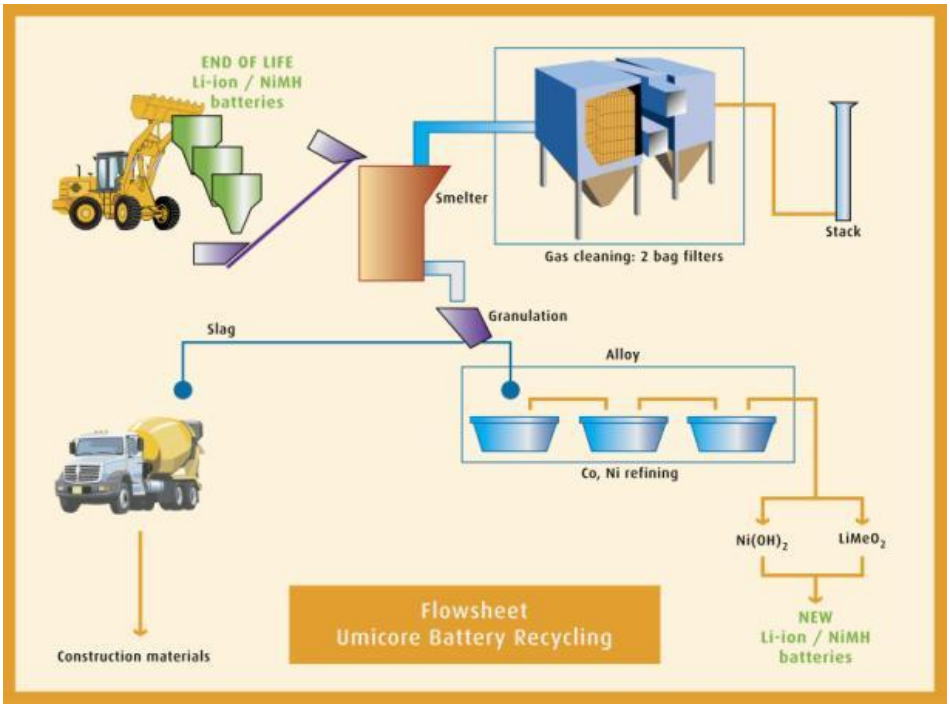


FIGURE 2. Umicore Battery Recycling Process Flows

**Physical recycling processes:** This approach to battery recycling is by its nature a low-energy process. Very little if any heat is employed; the energy that is required is used for running shredders and pumps and for producing liquid nitrogen. An example of this approach, the Toxco recycling system, is shown in Figure 3 [Coy, 2009]. Toxco's approach involves separating batteries by chemistry, shredding (reducing size) them in a flooded hammer mill, and separating product streams through a combination of a shaker table and two filters. Depending on the feed, liquid nitrogen is used only in two special circumstances: (1) to suppress potential ignition of electrolyte in discarded batteries with high residual energy and (2) to achieve better materials separation when certain battery potting materials were used.

The Toxco system produces three product streams: (1) mixed materials comprised of steel, paper, and plastics; (2) intermediate materials made up of collector foils, mixed metallics, and a little electrode material; and finally (3) a slurry of cathode and anode materials, some of which is carbon. Streams 2 and 3 are of the most value. Substantial amounts of copper, cobalt, nickel, and aluminum are contained in stream 2. Stream 3 produces two fractions: one that contains primarily a cathode material and anode carbon mix, which is rich in cobalt (35% by weight), and the second is a filtrate, from which lithium carbonate ($Li_2CO_3$) is recovered. This is currently used for other products, but could be purified for use in batteries.

The EcoBat process (OnTo/RSR) [Sloop, 2009] also employs physical separation (Figure 4). However, the developers have demonstrated methods on the bench scale to directly extract battery electrolytes, cathodes, and anodes from batteries for use in new batteries after minimal treatment. Pre-sorting is required to yield cathode material with a single composition.

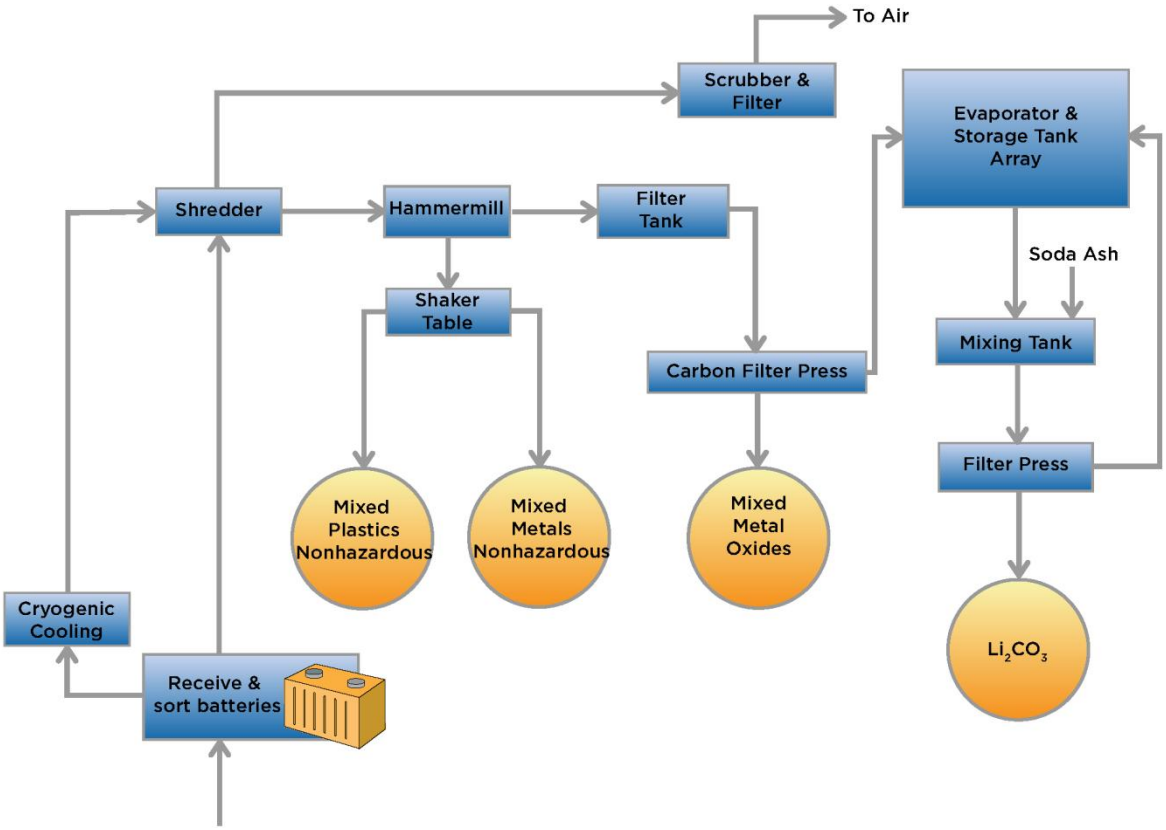


FIGURE 3. Depiction of the Toxco Recycling System

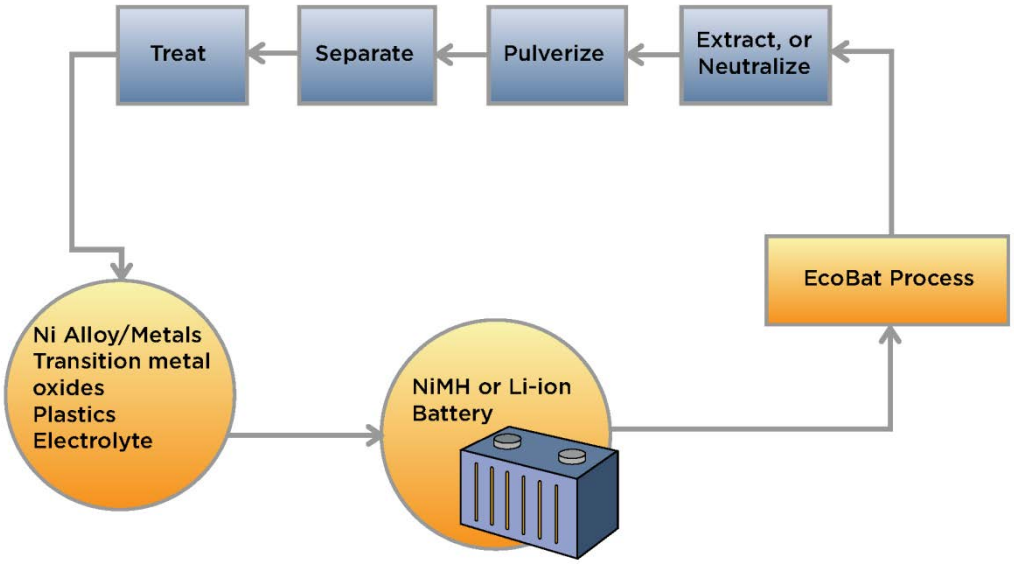


FIGURE 3. EcoBat Recycling Scheme

**Chemical recycling processes:** This approach can include hydrometallurgical and solvent extraction methods. Hydrometallurgical approaches use leaching methods to extract metal salts from process streams, such as ores, beneficiated ores, mill tailings, recyclates, and others, by means of acids or bases. For example, cobalt can be leached from the slag of a copper smelter. Solvent extraction methods can also be used in battery recycling. For example, the EcoBat process uses supercritical $CO_2$ to extract the electrolyte (e.g., diethyl carbonate) from lithium-ion batteries.

**Mixed methods**: If a particular element were traced through its first application lifetime to its next, the recycling scheme involved would likely consist of a mix of physical, chemical, hydrometallurgical, and pyrometallurgical processes. For example, a battery recycler might employ a pyrometallurgical process to capture metallic materials, but then for refinement purposes send some materials to another one of its operations for hydrometallurgical processing. Umicore is an example of such a company. The alloy (Cu, Co, Fe, and Ni) produced in its pyrometallurgical process is refined and purified by using a sulphuric acid leach with subsequent pH adjustments and dissolutions. The two primary products from their operations are nickel sulfate ($NiSO_4$) and $CoCl_2$.

Not all recycled battery materials are used in new batteries. Umicore focuses on Ni and Co that could be used in new batteries or other products after refining; Toxco's material outputs could similarly be used for batteries or as raw material substitutes in other products after further processing, depending on market demand.

## Energy Benefit of Recycling Battery Materials

In a recent report, Sullivan and Gaines [2010] reviewed life cycle studies in the literature for five battery systems. Three of those systems are addressed here: lead acid, nickel metal hydride, and lithium-ion. For a detailed discussion of material and battery production energies, emissions data, and compositions of these batteries (and two others), the reader is referred to that reference. Because our objective is to provide estimates of the impact of battery recycling on battery production energy ($E_{ctg}$), we present in Table 1 the production-stage energy components for the cradle-to-gate production of the three batteries mentioned above. The CTG battery production energy is the sum of two components: (1) process energies, $E_{mp}$, required for battery material production and (2) manufacturing energies, $E_{mnf}$, needed to produce components (cathodes, anodes) from those materials and assemble them into a purchase-ready battery. These components are primary energies. The former includes the production of commodity materials, such as lead, nickel, polypropylene, lithium carbonate, and others shipped to a battery manufacturer for making batteries. Energies needed to make materials unique to the battery industry (e.g., lithium cobalt oxide) are attributed to $E_{mnf}$. The first three rows of energy data in Table 1 are average values of energy data taken from Sullivan and Gaines [2010]. Battery compositions and other details can also be found there. These averages were generated by using only results where both material production and battery manufacturing data are provided in the original references.

Except for the lead acid battery, material production energy values shown in row 3 of Table 1 represent virgin materials only. The lead acid battery result shown there represents current practice, which ranges from 60% to 80% recycled lead in new batteries. For lead acid batteries, recycling is very mature. Further recycling of lead in these batteries offers at best another 15% reduction in material production energy with an associated 10% reduction of CTG energy. On the other hand, if lead acid batteries were made from only virgin lead, the material production energy would be 35% higher than that shown in the table, and its CTG counterpart would be 24% higher. Clearly, lead acid battery recycling offers considerable savings in both valuable metal and energy. For these calculations and others shown below, we focus only on metal recycling.

**TABLE 1. Estimated Influence of Recycling on CTG Energy Components in MJ per kg (Wh) of battery, $E_{mp}$, $E_{mnf}$, and $E_{ctg}$ for Three Types of Batteries**

| Battery | Lead Acid | Nickel Metal Hydride | Lithium-ion |
|---|---|---|---|
| Energy | | | |
| $E_{mp}$ — Current | 21[a] (0.50) | 88 (1.04) | 90 (0.90) |
| $E_{mnf}$ | 10 (0.24) | 113 (1.34) | 79 (0.79) |
| $E_{ctg}$ | 31 (0.74) | 201 (2.36) | 169 (1.69) |
| %$E_{ctg}$ for electricity [Rydh *et al.*, 2005] | 65 | 68 | 75 |
| $E_{mp}$ — Recycled | 17.8[b] (0.42) | 52[c] (0.61) | 64[d] (0.64) |
| % change in $E_{mp}$ | -15 | -40 | -28 |
| % change in $E_{ctg}$ | -10 | -18 | -15 |

[a] 30/70% virgin/recycled lead; [b] 0/100% virgin/recycled lead; [c] Recycled nickel, steel, polymer; [d] Recycled cobalt, steel, polymer

Also presented in the table are estimates of the percentages of $E_{ctg}$ that are used to make electricity for battery production. As our grid becomes less carbon intensive through greater deployment of renewable and nuclear assets, the carbon footprint will decrease for the production of these batteries. (See Sullivan and Gaines [2010] for a listing of other references that speciate battery production energies.)

If recycled nickel, steel, and polymer are used in making nickel metal hydride batteries, there is a 40% decrease in the material production energy and a concomitant 18% reduction in the CTG battery production energy. Given the magnitude of the production energy for these batteries, this is a substantial savings. If recycled mischmetal could be used, this reduction could be even larger. Unfortunately, information on mischmetal production from either virgin or recycled sources is limited. At this time, very little recycled Ni is actually used in the production of new nickel metal hydride batteries. Most of it is captured as an alloy with iron (ferro-nickel) and ends up in the stainless-steel stream.

Reliable values of the production energy for lithium-ion batteries are scarce. Some values have been published; a discussion of them appears elsewhere [Sullivan and Gaines, 2010]. Using averages of those values and assuming that recycled cobalt has 30% of the production energy as virgin metal (grey literature comments by Umicore), Table 1 shows a 28% reduction in material production energy and an associated 15% reduction in CTG production energy. We also assumed recycled steel and polymer. However, these estimates must be considered as approximate. With the exception of lead acid batteries, life cycle data for the manufacturing of advanced batteries (nickel metal hydride, lithium-ion, and others) and their constituent materials are found to be highly variable and inadequately described.

The estimates presented in Table 1 are intended to represent current practice. However, even better reductions might be possible. For example, if nickel metal hydride and lithium-ion batteries were comprised of not only recycled cathode and anode materials but also recycled steel (battery case) and polymer (separators), their production energies would be even less than cited above. Unfortunately, the mischmetal anodes of nickel metal hydride batteries require considerable material production energy, and no commercial recycling scheme for them has yet been identified. On the other hand, the EcoBat process discussed above might effectively recycle anode graphite from lithium-ion batteries. The production of anode graphite is very energy intensive, requiring extended baking at temperatures as high as 1100$^{o}$C.

A trend to be noticed in Table 1 is the relative magnitude of battery manufacturing energy. For nickel metal hydride and lithium-ion batteries, it represents about half of their CTG values, and for lead acid, it is about a third. Hence, material recovery will generally have limited — although substantial — impact on

battery life cycle metrics. However, there might be an opportunity to reduce battery-manufacturing energy somewhat if battery structures like cathodes and anodes are recovered and refurbished.

Energy is not the only environmental burden tracked in an LCI. Greenhouse gases and carbon dioxide, in particular, are also import burdens to be followed. However, because of the carbon intensity of our energy infrastructure, relative changes in carbon dioxide emissions more or less mirror those realized for energy. Hence, the recycling-induced percent changes cited in Table 1 for energy are representative of those for carbon dioxide. On the other hand, sulphur dioxide emissions are very significant for nickel refining, primarily because of the metal's extraction from sulfide ores. Although presumably controlled, these emissions (3.1 g/Wh of battery) are about an order of magnitude larger [Sullivan and Gaines, 2010] than the associated process-related combustion emission (0.27 g/Wh). The former of these two emissions is avoided by recycling nickel. Further, for a battery electric vehicle fitted with a suitably sized nickel metal hydride battery, these $SO_x$ emissions have been shown [Gaines *et al.*, 2002] to be larger than either those associated with either vehicle production or vehicle operation.

At present, batteries are being recycled. The lead acid battery example is a great success story. Battery plastics, acid, and lead materials are all recovered and used in new products, such as plastic moldings, detergents for the paper industry, and lead products. Some applications of the latter include batteries, computer circuit boards, lead chemicals, oxides for glass, and x-ray machine shielding. Nickel metal hydride and lithium-ion batteries are also being recycled, but not as completely as lead acid batteries. Battery metals (such as steel, nickel, cobalt, copper, and some other metals) are recycled, but organic constituents are not. Further, mischmetal in nickel metal hydride batteries and the lithium in lithium-ion batteries are not being recycled. Of the electroactive metals being recycled from these batteries, it appears that only the cobalt is returned to battery application. Nickel usually ends up as ferro-nickel and is used in stainless steels. However, a major auto manufacturer just announced battery-to-battery recycling for nickel metal hydride batteries, but there is no mention of recovering the metal hydrides [Recycling Announcement, 2010].

## Conclusion

We have estimated the impact of recycling on battery production life cycle energy. For lead acid batteries, recycling is mature and has resulted in substantial reductions in both cradle-to-gate battery production energy and $SO_2$ emissions. For these batteries, only marginal opportunities remain available for even further recycling-based reductions. For lithium-ion and nickel metal hydride batteries, more current and better-documented life cycle data are sorely needed. Nonetheless, our estimates show that reductions in CTG energy of at least 15–20% can be realized, with substantially larger reductions possible when recycling of their anode materials becomes practicable. Battery production energies are a substantial component of CTG energy values, ranging from around half for lithium-ion and nickel metal hydride batteries to a third for lead acid systems. But despite the lack of LCI data for advanced batteries like nickel metal hydride and lithium ion, these batteries and lead acid ones are being recycled.

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