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Life-Cycle Analysis for Lithium-Ion Battery Production and Recycling

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ABSTRACT

This paper discusses what is known about the life-cycle burdens of lithium-ion batteries. A special emphasis is placed on constituent-material production and the subsequent manufacturing of batteries. Of particular interest is the estimation of the impact of battery-material recycling on battery manufacturing. Because some of the materials come from comparatively less plentiful resources, a discussion is presented on the recycling of these batteries and its potential impact on battery-production life-cycle burdens. This effort represents the early stage of lithium-ion battery life-cycle analysis, in which processes are characterized preparatory to detailed data acquisition. Notwithstanding the lack of data on battery-materials production, we estimate that the energy use and greenhouse gas emissions associated with battery manufacturing make up only a few percent of a plug-in hybrid vehicle's total life-cycle energy use. Further, the recycling of battery materials can potentially significantly reduce the material production energy.

INTRODUCTION

Concerns about energy security and climate change have spurred a renewed interest in improving energy efficiency. One of the ways that has been advanced to address these concerns is to electrify personal transportation. As evidenced by recent development initiatives on the part of both government and the auto industry, advanced batteries are seen as an important enabler for manufacturing and marketing electric-drive vehicles, whether they be battery electric vehicles or plug-in hybrid electric vehicles (PHEVs). The successful deployment of viable battery systems for electric-drive vehicles can reduce oil consumption and greenhouse gas (GHG) emissions, depending on how the electricity is produced. However, the battery technologies required to provide traction in vehicles with practical driving ranges between rechargings represent a significant departure in material composition and performance from the lead-acid batteries found in conventional vehicles. As a result of these differences, much has yet to be determined concerning the system-wide performance of electric-drive vehicles and the contribution that batteries make to it. Nonetheless, it is clear that batteries with high specific energies and cycle lives are key factors in successful penetration of electric-drive vehicles into the marketplace, and lithium-ion (Li-ion) batteries are considered by many as the best near-term technology.

The market viability of electric-drive vehicles is multi-faceted, including affordability, consumer satisfaction, and engineering performance. However, environmental performance of such vehicles is also very important, and is one of the primary reasons for their development in the first place. Owing to the concerns cited above, the two most germane components of environmental performance for vehicles are energy use and emissions, especially fossil-carbon emissions. Because the electric-drive vehicle product system is a departure from its conventional counterpart, there are trade-offs that need to be elucidated. For example, the energy trade-off that needs to be quantified in building conventional vehicles using lightweight materials is the balance between the extra energy almost always incurred in making the lightweight material for the vehicle and the energy saved in propelling it owing to its reduced weight (*1*). In the case of electric-drive vehicles, a battery and some new powertrain hardware are replacing a fuel tank (with fuel) and some conventional powertrain hardware. Whether or not batteries constitute a significant fraction of vehicle mass, the energy use and emissions associated with the production of advanced batteries and their constituent materials need to be characterized and quantified to identify potential problems in advance.

As with any product system, the life-cycle burdens of batteries come from several life-cycle stages, including material production, battery production and use, and finally battery recycling. For electric-drive vehicles, battery production is a component of the life cycle, in the same way that fuel production is a component of a conventional vehicle's life cycle. Unfortunately, much has yet to be learned about the life cycles of batteries, especially Li-ion batteries. For example, little information is available on the burdens incurred in making lithium-constituent materials like lithium cobalt dioxide, lithium nickel dioxide, lithium iron phosphate, lithium hexafluorophosphate, diethyl carbonate, and numerous others. In some cases, even process information is not at hand. This absence makes it very difficult to estimate production energy and emissions based on life-cycle information for similar materials.

This paper summarizes what is known about the life-cycle burdens of lithium-ion batteries, especially the active materials that have not been well characterized up to now. Of particular interest is the estimation of the impact of battery recycling on the production of these materials. While most of the discussion focuses on energy, other impacts are noted when they are significant. GHG emissions can be calculated from the energy data. The potential impact of recycling on battery production life-cycle burdens is presented. Finally, recommendations for additional research needed to fill the information gaps on the life cycles of Li-ion batteries are discussed.

MATERIALS IN A BATTERY AND AVAILABLE LIFE-CYCLE INFORMATION

Life-cycle analysis (LCA) is a useful technique to compare alternative technological options; it involves taking a system-wide perspective of a product or service, by considering 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, a life-cycle inventory (LCI). The GREET 2.7 model developed by Argonne (*2*), which calculates energy use and emissions over the vehicle life cycle (vehicle material production, fabrication, assembly, disassembly, and recycling), is used in this paper to help examine the burdens of Li-ion batteries.

In order to characterize the potential environmental burdens of a Li-ion battery, we need to examine the material composition. Numerous chemistries are being developed, all of which offer trade-offs in cost, safety, and performance, e.g. cycle life, specific power, and specific energy (*3, 4, 5*). Gaines and Nelson (*6*) analyzed four batteries (shown in Table 1, with detailed composition data) for a PHEV20. The designation PHEVx refers to a plug-in hybrid with a nominal all-electric range (AER) of x miles. We selected the PHEV20 as our baseline vehicle because recent work (*7*) showed that this is the most cost-effective vehicle. Actual market introductions in the near future will be both above that range (Chevrolet Volt, 40-mi AER) and below it (Plug-in Prius, 14-mi AER); nonetheless, battery material quantities will more-or-less scale with AER. Roughly half of each battery's weight consists of materials (aluminum, steel, copper, plastics) that have been extensively documented in previous analyses (e.g., *8, 9, 10*) and which are included in GREET 2.7. Therefore, we will refer to that work for analyzing those materials' burdens and focus this paper on the other battery materials (highlighted in Table 1) that are not as well-characterized. GREET 2.7 will be updated as data on energy use and emissions of these less-well-characterized battery materials become available and are analyzed.

TABLE 1 Material Composition of Selected Li-ion Battery Systems for a PHEV20[a]

Battery	NCA-Graphite	LFP-Graphite	LMO (Spinel)-Graphite	LMO (Spinel)-TiO
Cathode	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	$LiFePO_4$	$LiMn_2O_4$	$LiMn_2O_4$
Anode	Graphite	Graphite	Graphite	$Li_4Ti_5O_{12}$
Battery mass (kg)	75.9	81.6	62.6	106.2
Material Composition (mass %)				
Cathode active material	24.8%	22.2%	24.4%	28.3%
Anode active material	16.5%	15.3%	16.3%	18.9%
Electrode Elements				
Lithium[b] (Li)	1.9%	1.1%	1.4%	2.8%
Nickel (Ni)	12.1%	0.0%	0.0%	0.0%
Cobalt (Co)	2.3%	0.0%	0.0%	0.0%
Aluminum (Al)	0.3%	0.0%	0.0%	0.0%
Oxygen (O)	8.3%	9.0%	12.4%	22.3%
Iron (Fe)	0.0%	7.8%	0.0%	0.0%
Phosphorus (P)	0.0%	4.4%	0.0%	0.0%
Manganese (Mn)	0.0%	0.0%	10.7%	12.4%
Titanium (Ti)	0.0%	0.0%	0.0%	9.8%
Graphite (C)	16.5%	15.3%	16.3%	0.0%
Carbon	2.4%	2.1%	2.3%	4.5%
Binder	3.8%	3.4%	3.7%	4.5%
Copper parts	13.3%	13.8%	13.5%	2.6%
Aluminum parts	12.7%	13.3%	12.5%	13.7%
Aluminum casing	8.9%	9.4%	9.2%	8.8%
Electrolyte solvent	11.7%	14.2%	11.8%	13.4%
Plastics	4.2%	4.6%	4.5%	3.6%
Steel	0.1%	0.1%	0.1%	0.1%
Thermal insulation	1.2%	1.3%	1.2%	1.2%
Electronic parts	0.3%	0.3%	0.4%	0.2%

[a] Table based on Ref. (*6*).
[b] Includes lithium salts in electrolyte.

Table 2 lists available published LCA information for some of the materials shown in Table 1. Most of the available information concerns the production of the elements needed for the compounds that make up the electrodes. Clearly, much more information is needed, as there are limited data on Li, Co, Ti, Mn and several others. No LCA data are available for the production of the electro-active materials, such as $LiCo_{1/3}Ni_{1/3}Mn_{1/3}O_2$, from their elemental precursors, salts, and oxides. Because many of these production processes are conducted at high temperature, these reactions require considerable energy, generally supplied by fossil fuels. A discussion of existing life-cycle information on Li-ion and other batteries can be found elsewhere (*11*).

TABLE 2 Life-Cycle Energy Values, Assessment and Sources for Li-ion Battery Materials (Y = yes, N = no, Min= minimal)[a]

Material	Production Energy (MJ/kg)	Energy Detailed?	Process Detailed?	Reference
Ni Ore → Ni	186	N	N	*12*
"	167	Y	Y	*13*
"	224	Y	Y	*14*
"	148	Y	Y	GREET 2.7
Ni-recycled	37	Y	Y	GREET 2.7
Ore → $Ni(OH)_2$	193	Y	Y	*13*
Ni → $Ni(OH)_2$	33	Y	Min	GREET 2.7
"	76.7	N	N	*15*
"	90.6	Y	Y	*13*
Co-precipitation	144	Y	Y	*13*
Brine → Li_2CO_3	44.7	Y	Y	*b*
Ore → $LiOH\text{-}H_2O$	163	Y	Y	*13*
Pet. Coke→ Graphite	187	Y	Y	*13*
Nylon	120	Y	Y	*16*
Polypropylene	80	Y	Y	*16*

[a] Source: Ref. (*11*)

[b] Argonne National Laboratory, unpublished data.

PRODUCTION PROCESSES FOR ACTIVE MATERIALS

Lithium Carbonate from Salars

The two resources from which lithium is extracted are spodumene and brine-lake or salt-pan deposits. For economic and energy-consumption reasons, the latter of the two is the more viable resource, and could meet a greatly increased demand for lithium used in automotive traction batteries (*6*). The extraction process is straightforward: brines are pumped from underground brine wells or lake beds into a solar evaporation pond and allowed to concentrate. After sufficient evaporation, the brine is pumped to another pond until sodium chloride crystallizes and precipitates. The brine is pumped to a succession of ponds, where at each step more sodium chloride (or other salts) is precipitated. After 4 or 5 ponds, slake lime is added to precipitate Ca and Mg salts, producing gypsum and magnesia. Further additions of slake lime and successive transfers to additional ponds deplete the sodium, calcium, and magnesium salts, until finally a brine with 0.5% lithium can be transferred to a processing plant where the lithium is extracted as lithium carbonate. Our energy assessment shows that 40.2 MJ of purchased energy, including that associated with the production of lime, is required to produce a kg of Li_2CO_3. This value corresponds to a life-cycle energy rate, including the fuel cycle of purchased fuels, of 44.7 MJ/kg. Most of the purchased energy (78%) is derived from fuel oils; about 4% is from propane, and the remainder mostly from coal.

Lithium from Spodumene

Another lithium source is spodumene, which is a mineral consisting of lithium aluminum inosilicate - $LiAl(SiO_3)_2$. Production from minerals was abandoned when less costly production from salars was introduced. However, producers are considering production from minerals again, to increase and diversify supply and re-enable domestic U.S. production. One reason for the higher cost is the higher energy requirement associated with the process. In addition to mining and milling the ore, the mineral spodumene must be treated at 1000^oC to achieve the structural transformation from an alpha to a beta form to enable acid leaching using sulfuric acid. Lithium is then recovered in the form of lithium salts.

Cathode Production

Most of the available cathode materials are made by calcination at high temperatures of mixtures of lithium carbonate and transition-metal precursors. Lithium hydroxide is also used; however, special handling is required during the process of mixing. Solid-state reactions at temperatures in the range of 600 to 800^oC are typically required to obtain suitable structures and achieve maximum crystallization. Fossil fuels are required for this process. The structural and physical properties, such as morphology and packing density, of the final materials are the key factors in determining whether a material can be used as a positive electrode for Li-ion cells. Table 3 lists precursors for several cathode materials.

TABLE 3 Cathode Materials and Precursors

Cathode Material	Lithium Source	Other Reagent(s)	Atmosphere
$LiCoO_2$	Li_2CO_3	Co_3O_4	air
$LiNi_xCo_yMn_zO_2$ $(x+y+z=1)$	Li_2CO_3	$Ni_xCo_yMn_z(OH)_2$ $(x+y+z=1)$	air
$LiMn_2O_4$	$LiCoO_2$	Mn_2O	air
$LiFePO_4$	Li_2CO_3	$NH_4H_2PO_4$, $FeC_2O_4{\cdot}2H_20$	neutral
$LiFePO_4$	Li_2CO_3 or LiOH	FePO4	neutral

Anode Production

Carbonaceous anodes have different forms in Li-ion batteries. Natural graphite, hard carbon, soft carbon, and mesocarbon microbead are widely used for lithium insertion anodes in commercial cells. All synthetic graphite materials require 2700˚C for full graphitization, so this process is energy-intensive, using fossil fuels. Recently, coating with very thin layers of amorphous carbon has emerged as a viable way to protect the surface of carbonaceous anodes against deterioration under cell working conditions. This process uses gas-phase sources, such as propylene or methane, which need to be cracked at 700^oC in the presence of graphite. Lithium titanate ($Li_4Ti_5O_{12}$) material recently gained tremendous attention as a high-power anode material to replace graphite anodes in Li-ion cells where energy is less of an issue. It is produced by reacting lithium carbonate (Li_2CO_3) and titania (TiO_2 in its anatase crystalline form) at 850^oC under air. This process requires less energy than graphite production.

BATTERY ASSEMBLY PROCESSES

Typical processes used for production of small commercial Li-ion cells (size 18650) are described here. Essentially the same processes could be used for production of larger cells for electric-drive vehicles. A block diagram of battery manufacture is shown in Figure 1. Electricity use for these operations makes up a significant fraction of battery production energy.

1. A cathode paste is made from purchased $LiCoO_2$ powder (80-85%), binder powder, solvent, and additives in a chemical vessel and pumped to the coating machine.
2. Coating machines spread the paste to a thickness of about 200 to 250 µm on both sides of the Al foil (about 20 µm thick, purchased in rolls). Drying reduces the thickness by 25-40%. The coated foil is calendered to make the thickness more uniform and then slit to the correct width.
3. Graphite paste is produced in a process similar to that used for the cathode paste and then spread on Cu foil to produce the anodes. A small amount of material is trimmed off the edges of the foils. A small amount of material is also lost when a new roll of foil is spliced in, because the taped area must be cut out. This material can be sent to recycling.
4. The anode, separator, and cathode layers are wound up and inserted into cylindrical or rectangular cases.
5. Cells are filled with electrolyte, purchased premixed from a chemical house.
6. Insulators, seals, valves, safety devices, etc., are attached, and the cells are crimped closed (or welded).
7. Cells, fabricated in a fully discharged condition, are charged by using a “cycler.” These cyclers will have to provide high current for electric-vehicle batteries. Cells are conditioned and tested: they are charged, left on the test stand for several days, and then discharged, and this cycle is repeated four times to verify product quality. Some energy is used for this step, and care is required to prevent fires, because of the large inventory of batteries being tested.
8. Cells are fitted with electronic circuit boards to control charging/discharging and packed into cases.
9. Defective cells (about 1%), non-homogeneous electrode materials, and leftover separator go to scrap. Scrap material can be sent for recycling.

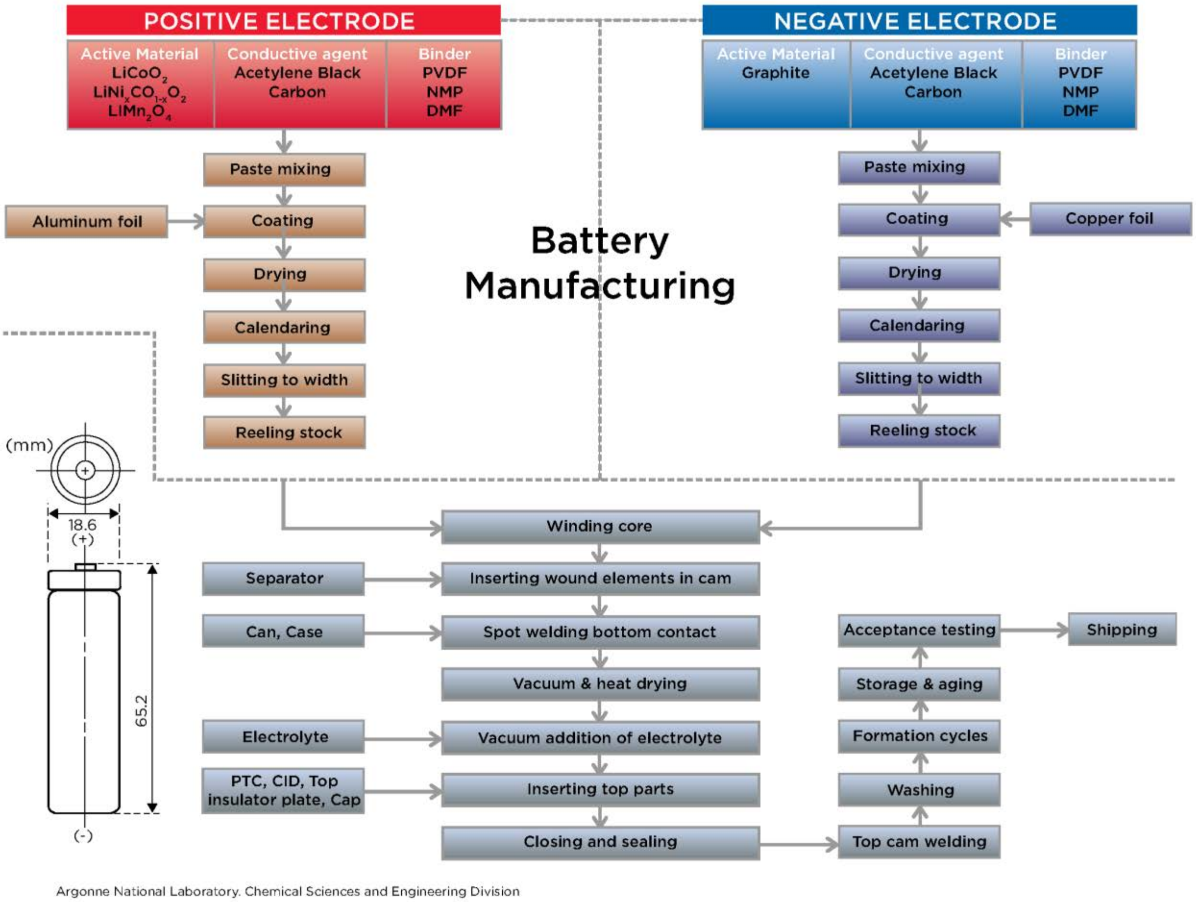

FIGURE 1 Schematic of battery assembly processes.

RECYCLING PROCESSES FOR LITHIUM-ION BATTERIES

Not all recycling is created equal, meaning that a process can be considered “recycling” even if it only recovers one useful product from a multi-component product or if the recycled materials go to lower-value uses (“downcycling”). Today’s battery recyclers must deal with a very diverse feedstock that includes numerous battery types and might even include harmful or dangerous components. Recycling consumer electronic batteries will keep the companies operating until the automotive propulsion batteries are available for recycling in large quantities. When automotive batteries finally arrive at these facilities, recyclers will find their job somewhat easier because the batteries will be larger, will probably come in a much smaller number of types or chemistries, and may even be labeled with bar codes to enable identification and machine sorting. Standardization and design-for-recycling would make the job even easier. Note also that current recycling processes are driven by the revenues from cobalt recovery. As Co use declines, other incentives will be required to make the business of recycling Li-ion batteries profitable.

Recycling can recover materials at different production stages, all the way from basic building blocks to battery-grade materials. At one extreme are smelting processes that recover basic elements or salts. These are operational now on a large scale and can take just about any input, including different battery chemistries (including Li-ion, nickel metal hydride, etc.) or mixed feed. Smelting takes place at a high temperature, and organics, including the electrolyte and carbon anodes, are burned as fuel or reductant. The valuable metals (Co and Ni) are recovered and sent to refining so that the product is suitable for any use. The other materials, including lithium, are contained in the slag, which is now used as an additive in concrete. The Li could be recovered by using a hydrometallurgical process, if justified by price or regulations.

At the other extreme, recovery of battery-grade material has been demonstrated. Such processes require as uniform a feed as possible, because impurities in feed jeopardize product quality. The components are separated by a variety of physical and chemical processes, and all active materials and metals can be recovered. It may be necessary to purify or reactivate some components to make them suitable for reuse in new batteries. Only the separator is unlikely to be usable, because its form cannot be retained. This alternative approach to battery recycling is a low-temperature process with a low energy requirement. Almost all of the original energy and processing required to produce battery-grade material from raw materials is saved.

Although many papers discuss recycling of Li-ion batteries, only three companies have actually provided enough information to be of any use in the present analysis. Of these, two are actually recycling batteries commercially, and one has demonstrated capability. These three processes are described below.

Umicore (Val’Eas Process)

Figure 2 is a simplified flow chart of the Val’Eas process (M. Caffarey, Umicore, July 2010, unpublished data). Umicore is a European company that processes all types of batteries in two locations. It collects spent batteries and ship them to its plant in Hofors, Sweden. The material collected is fed into the smelter with no pre-processing. Organic components in the batteries (plastics, electrolyte solvents, and carbon electrodes) are burned. Umicore counts this as recovery because the heat fuels the smelter and the carbon serves as a reducing agent for some of the metal. The main products are cobalt and nickel, which are then sent to a refinery in Olen, Belgium, where the $CoCl_2$ is made; it is subsequently forwarded to South Korea to produce $LiCoO_2$ for batteries (using new purchased lithium). Recovery of cobalt and nickel not only saves about 70% of the energy needed for their primary production from sulfide ores, but also avoids the significant SO_2 emissions from such production. Other metals, such as iron, can be recovered as well. The lithium and aluminum from the smelter currently go to the slag, which find low-value uses, but the company is investigating ways to recover lithium for higher-value uses such as batteries. Waste gases are subjected to high temperature to avoid emissions of dangerous organics like furans or dioxin. The company claims a 93% recovery rate for Li-ion batteries (metals 69%, carbon 10%, plastics 15%), but a much smaller percentage actually comes out as usable high-value material.

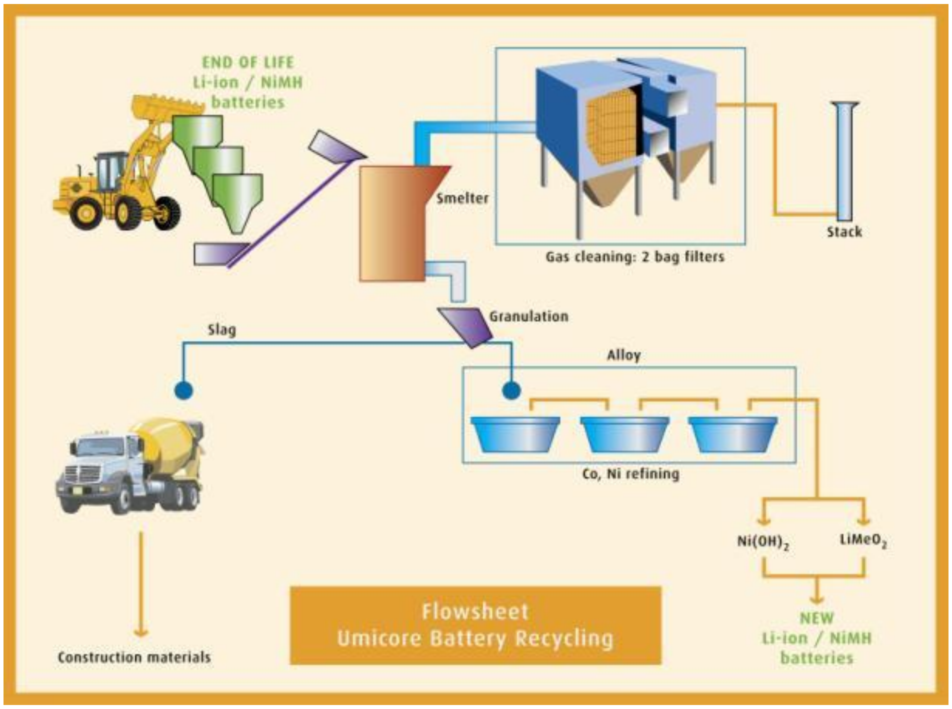

FIGURE 2 Umicore recycling process.

Toxco Process

The Toxco process has been in commercial operation since 1993, in Trail, B.C., Canada, processing Li-ion batteries of varying chemistry and other battery types. The company was given a grant in 2009 by the U.S. Department of Energy to recycle Li-ion batteries at its plant in Ohio. Toxco has demonstrated how automotive packs would be recycled by actually processing the pack from a Tesla Roadster. First, the battery pack was discharged for safety reasons, and the propylene glycol in the cooling tubes was recovered. The control circuits were removed and tested for possible reuse. The wires and some other metals were removed for recycling. The packs were disassembled and a series of mechanical processes, shown in Figure 3 (from Coy, T., Kinsbursky Brothers, Inc., July 2010, unpublished data), were used to reduce the size of the cell materials. The three resulting products were fluff, copper cobalt (yielding salable metals such as cobalt, aluminum, nickel, and copper), and cobalt filter cake (reused in appliance coatings). Soda ash was added to the resulting process solution to precipitate out the lithium carbonate.

The recycling process is mainly mechanical and chemical, so emissions are kept to a minimum. Since no high-temperature processing is required, energy use is also low. About 60% of the pack materials can be recycled, and a further 10% reused. The fluff, which comprises about 25% of the pack, will be landfilled initially, but the plastic will be recovered when the volumes are high enough to justify the effort.

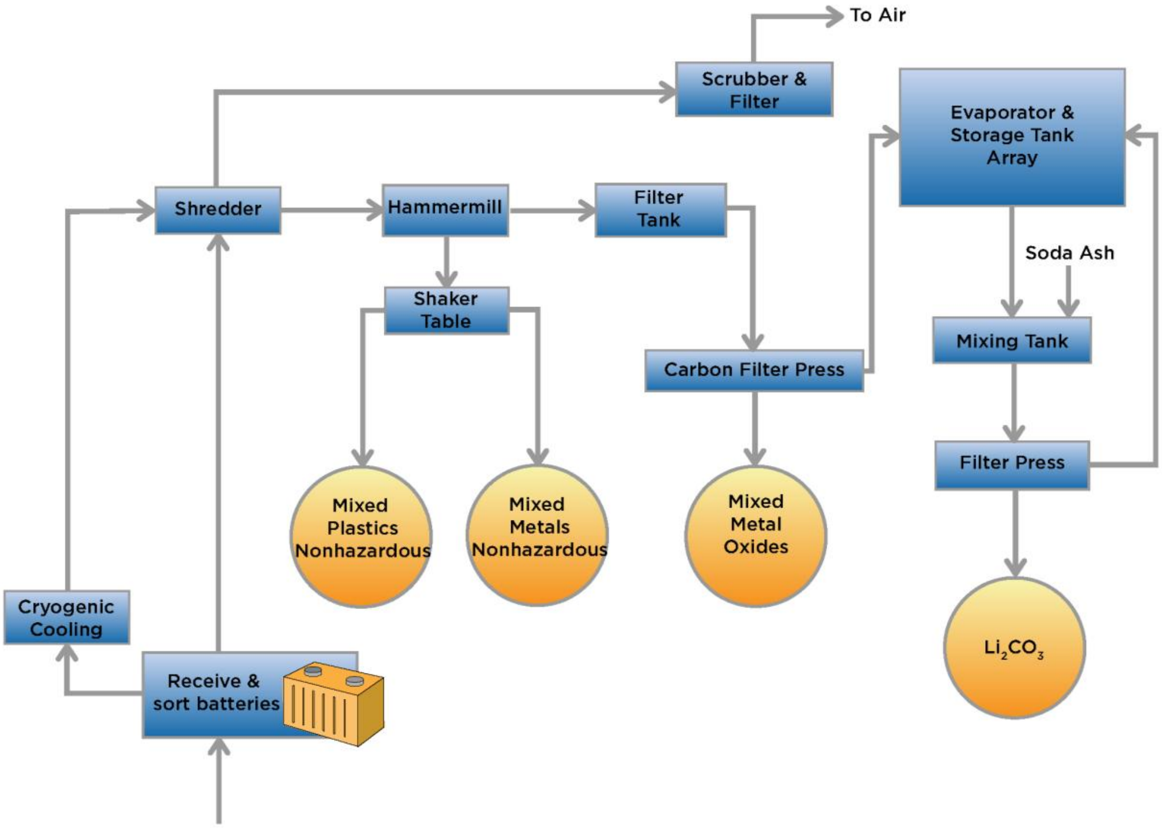

FIGURE 3 Toxco recycling process.

Eco-Bat Process

The Eco-Bat process was developed initially by OnTo, an Oregon company that holds several patents on this bench-scale technology and is now partnering with RSR, a major lead recycler in Texas. Energy requirements for the process are low. The developers have worked with the Vehicle Recycling Partnership and actually constructed new, functional Li-ion cells from spent consumer batteries (one type at a time). The electrolyte solvent and salts can be reused, as can the carbon anode and the lithium-salt cathode material, although some additional lithium carbonate may be required to relithiate the cathode material. The separator cannot be reused, but recycling the separator would be of limited utility, since its main value is in the processing required to get it into the correct physical configuration. Metal parts are recovered for recycling. Battery-pack containers could potentially be reused, depending on the configuration. This is a clear instance of potential for design-for-recycling (actually reuse here).

The process, shown schematically in Figure 4, requires minimal energy use, since there is no high-temperature processing. Many of the process details are proprietary, and so cannot be specified here. The first process step, for which the patent is available, involves violating the cell packaging just enough to allow fluids to be exchanged. The electrolyte is extracted using supercritical carbon dioxide. It carries the salts with it and can be reused. The CO_2 could be recovered from combustion waste. The remaining structure can then safely be chopped into small pieces that are amenable to a series of separation processes based on surface properties and solubility. The active-material structures are maintained, and the developers have demonstrated that new batteries can be produced from them with only minimal treatment. Over 80% of the material is actually recycled to useful products. Thus, the potential value of the recovered materials is quite high. The cost of recovered cobalt is well below the current market price for virgin material. The cycle life of a cell made with recycled material is excellent. Experimental results are excellent for both cobalt and phosphate cathodes (*17*). Of course, processing a mixed feed would require additional separation steps to yield high-quality final products. There is no obvious barrier to scaling up this process.

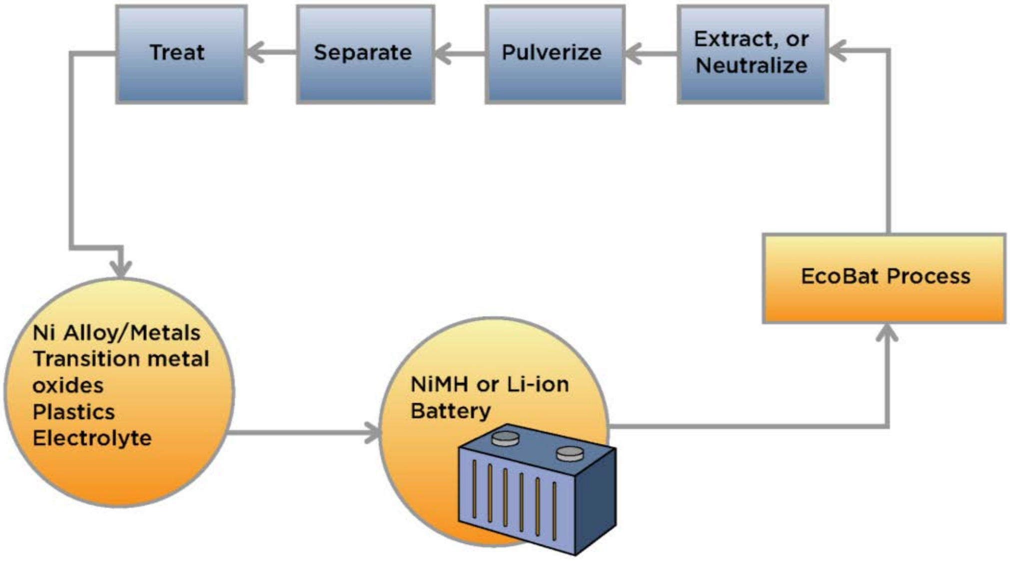

FIGURE 4 Eco-Bat process.

BATTERY PRODUCTION AND RECYCLING IN CONTEXT

Comparison to Total Life-Cycle Energy

A complete LCA includes not only an inventory of the energy use and emissions for a well-defined system, but also an analysis of their impacts. However, this paper focuses on development of an inventory representing the cradle-to-gate (CTG) life-cycle performance of Li-ion batteries. While there is considerable uncertainty regarding the production and associated impacts of several battery materials on the CTG inventory, we can still put battery production in context with the rest of the activities relevant to battery application, in this case electric-drive vehicles, by performing a total-energy-cycle analysis. The total energy cycle includes (a) the fuel cycle (well-to-wheels), which is comprised of two parts, the well-to-pump (or plug) (WTP) and (plug or) pump-to-wheel (PTW) steps, and (b) the vehicle cycle, which includes battery production. In order to investigate alternative fuels and advanced vehicle technologies, Argonne scientists developed the GREET 1 model to calculate the fuel-cycle energy use and emissions and the GREET 2 model to calculate the vehicle cycle.

Using the current versions of the fuel-cycle and vehicle-cycle models, GREET 1.8d.0 and GREET 2.7, respectively, we have examined the total energy cycle of a PHEV20. The fuel-cycle results are based on a model-year 2010 vehicle that in charge-depleting operation uses a blended-mode control strategy (maximizing fuel efficiency by using both the engine and battery power to drive the vehicle); the vehicle-cycle results are based on the results from Argonne's Powertrain System Analysis Toolkit and the NCA-graphite battery chemistry shown in Table 1. While there is uncertainty regarding the energy consumption of producing some battery materials, we have used GREET 2.7 to put battery production in context with the rest of the vehicle cycle and the fuel cycle. For materials that were not in the public version of GREET 2.7, we updated the lithium carbonate energy use using the value in this paper, while placeholder materials were used for the other less-well-characterized materials (generally chosen to have greater impacts than expected from the battery materials); in place of graphite/carbon, cobalt, binder, and electrolyte, we used carbon fiber, nickel, polyvinylidene fluoride, and Nafion, respectively.

In Figure 5, we see that the fuel-cycle (WTP [23%] and PTW [61%]) stages of the life cycle dominate the total energy use for this PHEV20. The vehicle cycle of the car minus the battery accounts for about 14% of the life-cycle energy use, while the battery only accounts for 2% (assuming a 160,000-mi lifetime and no battery replacement). Notter et al. (*18*) obtain similar results with all impacts aggregated into a single environmental "score." Nearly half the battery-production energy use is associated with assembly and testing, while well-characterized materials (aluminum, copper, nickel, and plastics) account for almost one-third. The other materials account for a relatively small percentage of the weight of the battery and of the energy consumption from a life-cycle perspective. Therefore, even with considerable uncertainty surrounding the production of these materials, they are a small part of the vehicle cycle, which in turn is a small part of the total energy cycle. While Figure 5 shows results in terms of energy, graphs showing GHG emissions would be quite similar.

Comparison of Recycling to Primary Production

From Figure 5, we see that a large percentage of the battery life-cycle energy, which is consumed during battery manufacturing using predominantly electricity, cannot be recovered by recycling. However, materials such as aluminum, nickel, steel, and copper illustrate the benefits of recycling, with percent reductions in energy consumption from about 25% for steel to 75% for aluminum and nickel (see Table 4). We estimated that potentially half the energy use for the less-well-characterized materials could be saved by recycling them. As these data are developed, we will add them to GREET 2.7. The "Increased Recycling" case illustrated in Figure 5(c) shows a 30% decrease in energy use versus the "Base" case of Figure 5(b). Emissions of SO_2 from primary metal smelting have also been avoided.

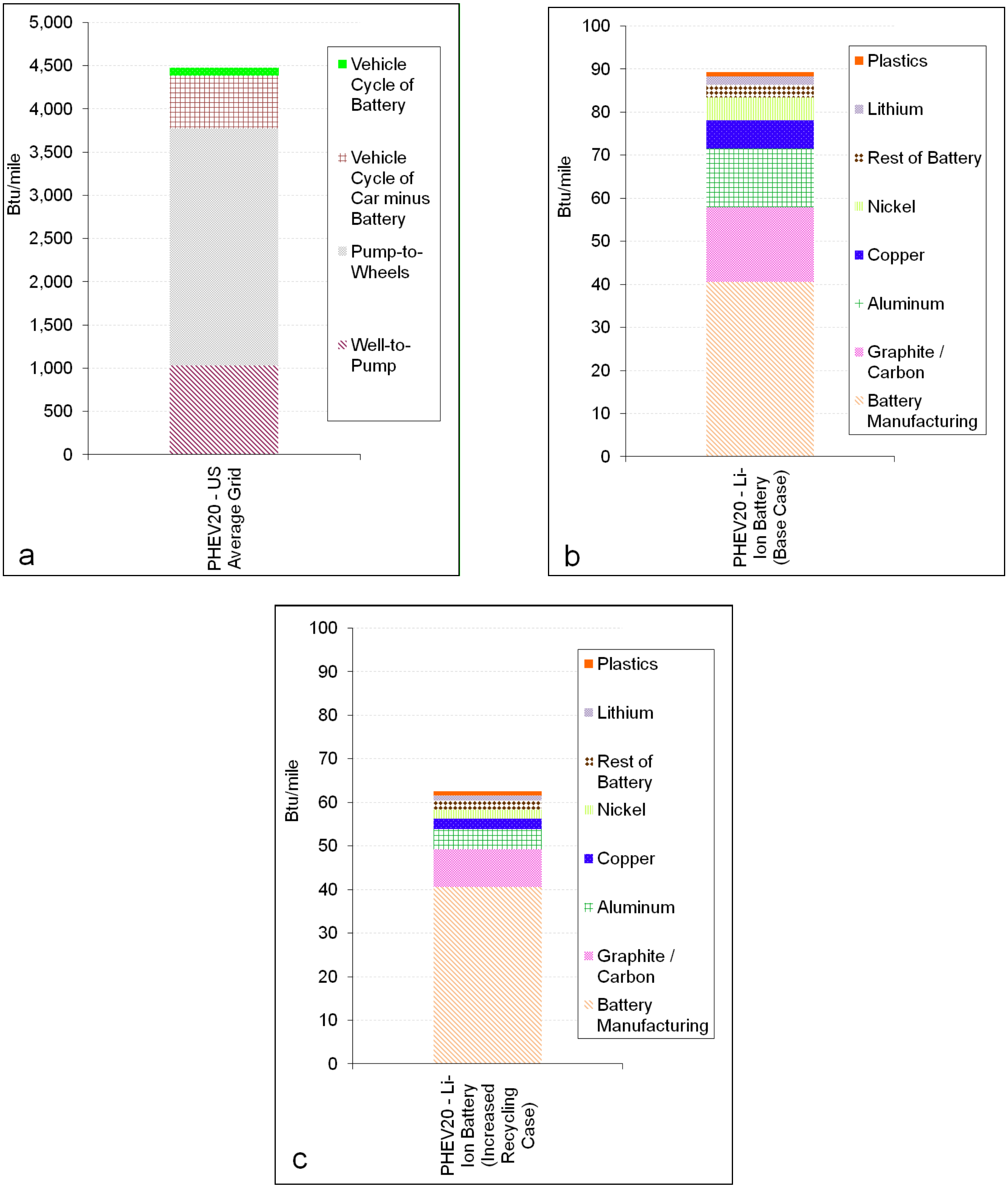

FIGURE 5 (a) Total energy cycle of a PHEV20; (b, c) battery life-cycle energy for (b) base and (c) increased-recycling cases.

TABLE 4 Life-Cycle Energy Consumption for Primary and Secondary Material Production[a]

	Primary Production (million Btu/ton)	Secondary Production (million Btu/ton)	% Reduction
Wrought aluminum	157.3	40.7	-74.1%
Cast aluminum	132.9	39.0	-70.7%
Nickel	124.7	31.2	-75.0%
Steel	38.6	29.1	-24.6%
Copper	94.2	34.3	-63.6%

[a] Sources: Ref. (*2*); GREET 2.7

CONCLUSION

The life-cycle energy performance of Li-ion batteries has been discussed. While there is considerable missing information on battery-materials production, estimates can nevertheless be made of the impact of the CTG battery inventory on a PHEV's total life cycle: i.e., it is small, on the order of a few percent. Further, the recycling of Li-ion battery materials potentially reduces the material production energy by as much as 50%. If battery active materials can be recycled in forms suitable for reuse with minimal processing, this percentage reduction could be even higher, as considerable energy is committed to making them from raw materials.

Quantitative information on process yields, byproducts, and emissions, as well as quantities and types of energy purchased for all process steps from virgin raw materials to precursors to active materials and finished batteries, as well as for recycling processes, would be required to complete the LCI. Further, both purity and crystal structure of the recycled materials must be determined to be suitable for reuse in batteries or other products. Processes for feed separation and/or product upgrading may be needed if we are to realize the full potential of Li-ion battery recycling.

This analysis was performed for a PHEV20. Two vehicles soon to be entering the market (the Volt, a PHEV40, and the Leaf, a 100-mi all-electric) will require approximately 200% and 500% as much material, respectively, and therefore will have a considerably larger footprint, magnifying the importance of recycling for both material supply and energy and environmental impacts.

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