IMPACTS OF THE MANUFACTURING AND RECYCLING STAGES ON BATTERY LIFE CYCLES

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Abstract

The life cycle of batteries includes five stages: 1) material production, 2) component manufacture and battery assembly, 3) battery distribution, 4) use, and 5) battery end of life. The first two of these stages represent the cradle-to-gate (CTG) components of the battery life cycle. This work focuses on stages one, two, and five and provides new information on the battery manufacturing stage, where anodes and cathodes are made and assembled with other components into batteries. This new battery production information has been derived from calculations of energy consumption of equipment at battery manufacturing facilities. As recycling doesn't necessarily reduce stage two impacts, stage two energy consumption data are especially important, as previous work suggests the magnitude of energy consumed during this stage may be comparable to energy consumed in the material production stage. Further, we consider advancements in battery recycling and how recycling process alternatives may affect the life cycle energy consumption of lithium ion batteries.

Introduction

Electric-drive vehicles are promoted as a critical part of moving the U.S. toward reducing its dependence on foreign oil and reducing greenhouse gas emissions from the transportation sector. Battery technology, especially lithium ion technology, is making advances that are increasing the viability of electric (pure and hybrid) vehicles (EVs). As EVs increase their presence in the domestic fleet, questions have arisen as to potential harmful impacts of the batteries that power them. Life cycle analysis (LCA) is a structured and quantitative approach to systematically examine the life cycle of batteries, identify high-emitting or energy-consuming stages, and gain an estimate for overall life-cycle energy consumption and emissions to the environment [1,2,3]. Figure 1 outlines the steps commonly included in LCA. Herein, we briefly summarize three published battery LCAs and then focus on two critical steps in the life cycle of lithium ion batteries that have been subject to uncertainty, the material production and component manufacturing and assembly stages.

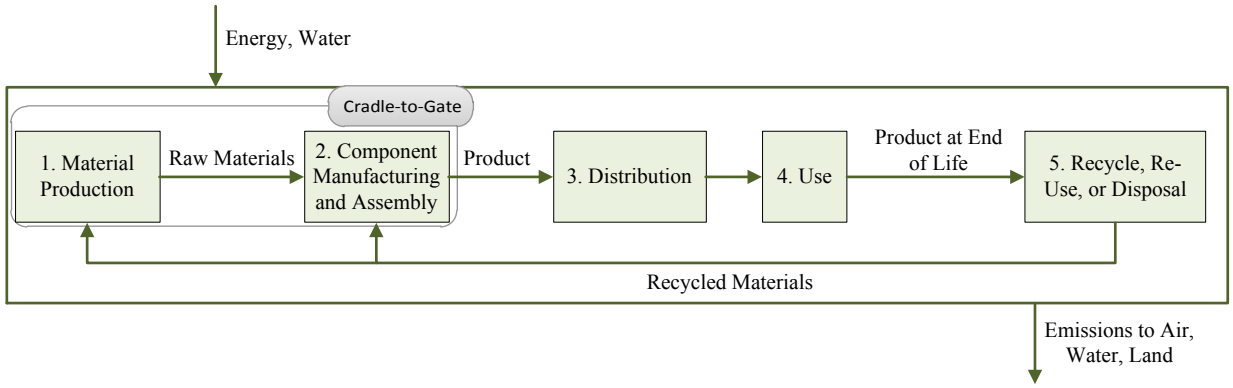

Figure 1. Commonly considered stages in life cycle analysis

Rydh and Sandén [4] developed cradle-to-gate (CTG) estimates of energy consumed in the life cycle of eight battery technologies, including cylindrical lithium ion batteries. Although the authors account for the reduction in energy in the first stage in Figure 1 that will come about from recycling and subsequent avoidance of acquiring and processing virgin raw materials, the authors do not estimate the energy required to recycle the batteries. Further, it is not possible from their analysis to extract the energy of the second stage in Figure 1. Notter et al. [5] do provide an estimate of the energy consumed during stage two, but do not include a recycling step in their analysis, assuming a scenario in which no recycling occurs and the full burden of raw material acquisition is assigned to each battery. Majeau-Battez et al. [6] provide a CTG energy consumption estimate and do not include a recycling step in their analysis.

In this paper, we take a closer look at the energy required to assemble a lithium ion battery from its component parts, or stage two in Figure 1, because there is concern that it is a significant contributor to life-cycle battery energy consumption. We also examine existing battery recycling processes and consider the effects of recycling on stages one and two in Figure 1.

Energy Intensity of Battery Manufacturing and Recycling

The energy intensity of battery assembly and recycling are uncertain [7]. In this section, we review key studies that have examined these parameters and present our estimate of this energy intensity.

Battery Manufacturing

Common structural materials (aluminum, plastics, steel, copper) comprise roughly half of a battery's mass. The cathode, anode, and separator are other key battery components. The cathode (positive electrode) material is a metal oxide, with lithium ions inserted into the crystal structure. Commercial electronics batteries generally use cobalt, but oxides containing nickel, manganese, and other elements are being developed for vehicle batteries. In this paper, we focus on a cathode chemistry of $LiMn_2O_4$, which is formed from heating lithium carbonate and manganese oxide in a kiln, quenching with water, then spray drying. Lithium carbonate is produced from salars (large brine lakes), mostly in Chile. Brines are concentrated in ponds for over a year, then treated with soda ash. The carbonate precipitates, and is filtered out and dried.

The anode (negative electrode) is generally made of graphite. To eliminate detrimental oxygen-containing species on the surface, it is baked at 2,000°F (1,100°C) in a reducing or inert atmosphere.

Argonne's LCA of lithium ion batteries is based upon a model of lithium ion battery assembly that Nelson et al. developed [8]. This peer-reviewed model provides an inventory of battery components and describes the equipment and steps involved in assembling these components into a battery at a manufacturing facility. In this model, batches of electrode materials including active carbon, binder, and binder solvent are mixed together in tanks. The resulting mixture is pressurized, pushing the coating paste into the coating mechanism. The electrode materials are spread onto thin metallic foil substrates, which also serve as the current collectors. For the cathode, aluminum foil (about 20 μm thick) is used, and for the anode, copper (about 14 μm thick).

After this coating process, rolling compresses the coating to achieve a desired void volume fraction, which will allow the electrolyte to permeate the coating. Then, slitters cut the electrode foils into strips, then into individual electrodes. Vacuum drying is the next step before cell assembly. The dried electrodes are unloaded into a dry room, where cell assembly occurs. Assembly in a low-moisture environment is likely key to achieving a long battery life. The Argonne model's dry room operates at a maximum dew point temperature of -40°C. In the dry room, cells are stacked, with the electrodes placed into a folded separator sheet. Separators for Li-ion batteries are typically made from polyolefins using 3- to 8-μm layers (Polypropylene/Polyethylene/Polyproplyene or else just polyethylene). The porous film keeps the electrodes apart, and if the cell becomes too hot, melts and closes off the pores, thereby shutting off the cell current. Next, the current collectors are welded and the cell is enclosed in a pouch container with an outer layer of polyethylene terephthalate, a middle aluminum layer, and an interior polypropylene layer.

Subsequently, the cells are evacuated, electrolyte is injected, and the cells are temporarily sealed. The electrolyte is lithium hexafluorophosphate dissolved in a blend of ethylene carbonate and another, linear carbonate. The next step is formation cycling in which the cells are charged, discharged to full depth, and then fully recharged. During formation cycling, cell capacity and impedance are monitored. Failed cells are rejected. The remaining cells are then sealed permanently. An additional long term test, the charge-retention storage test, identifies cells with abnormal self-discharge rates, which are also discarded. The Argonne model estimates the total discard rate at 5% of cells, from which recyclable materials are collected and shipped to recyclers. This model depicts one scenario for battery manufacturing; variations upon this scenario are possible and likely. For example, the dry room may incorporate the coating process in addition to the above-described steps.

In the Argonne model, one battery module requires 96 cells, which are surrounded with an aluminum heat conductor. An electronic circuit pack is attached. An air-tight aluminum container houses each module. Automated stations assemble the finished modules into battery packs, which undergo a final impedance check and charge lowering step.

Notably, electricity powers the majority of the equipment in this model, but some natural gas could be used in the drying of the coated anodes and cathodes. In real-world plants, residual oil may power boilers at some battery manufacturing facilities.

As the development of the lithium ion battery production matures, it may be that not all the steps in the Nelson et al. [8] model occur under one roof. For the time being, however, we assume that the steps occur at one facility and the energy associated with these steps constitutes the stage two energy. Relative to a multiple facility production scheme, the primary impact of this assumption on our final results is avoided transportation energy associated with shipping components to a final assembler. One key aspect of the model is the dry room. The equipment maintaining the dry room's conditions is likely a major energy consumer during manufacturing. A dry room manufacturer [9] provided a quote for a dry room (1,860 m^2) that two dehumidification systems maintain at a relative humidity of 0.5% at 21°C. The systems incorporate a desiccant wheel with indirect-fired natural gas reactivation, electric heating, and electric motors. We assume that energy consumption scales linearly with dry room area and adjust the energy consumption correspondingly for the dry room area in the Argonne model (2,000 m^2). The dry room consumes 1.30 MJ/kg battery with shares of electricity and natural gas of 39% and 61%, respectively. Another energy consumer is the formation cycling step. We assume only one charge and discharge cycle, which consumes 0.23 kWh/battery of electricity or 0.01 MJ/kg battery [10]. It is possible that some battery manufacturing facilities will use more than one charge and discharge cycle, but the energy consumption of this step is likely to be low, regardless. For our analysis, we estimate the dry room and cycling steps consume 60% of the total manufacturing energy [11]. The resulting stage two energy consumption is 2.2 MJ/kg battery.

The three above-described studies provide a basis for comparison for this result. The first, Rydh and Sandén [4], reported a CTG energy of 96-144 MJ/kg battery. Majeau-Bettez et al.[6], based upon Rydh and Sandén, provide a CTG energy of 84 MJ/kg. Notter et al. [5] isolate the battery assembly step (stage two only) and report it as 1.3 MJ/kg. Our analysis also isolated this stage and the results align well with that of Notter and co-authors.

Battery Recycling

Several processes to recycle batteries are currently in use or under development. The first of these is smelting, which Umicore employs to recover basic elements or salts [12]. Smelting, is a high-temperature process that burns organics to generate heat to fuel the smelter, has limited applicability for the recycling of lithium ion batteries with $LiMn_2O_4$ chemistry because lithium ends up in the smelter slag. Neither economic conditions nor regulations favor its recovery via hydrometallurgical processes. The current driver of the process is the recovery of nickel and cobalt. The cobalt, after further processing, can be incorporated into batteries with $LiCoO_2$ as the cathode. This recycling saves 70% from the energy needed for primary production of metal ores.

Other processes, which we call intermediate recycling processes, do allow the recovery of additional material. For example, the Toxco process uses a suite of low-temperature mechanical and chemical steps to separate out fluff, copper cobalt, and cobalt filter cake [12]. The addition of soda ash forces lithium carbonate out of solution for re-use. Simliarly, Recupyl's process

involves material shredding and recovers plastics, metals, and lithium carbonate by chemical precipitation; the latter is suitable for re-use in batteries [13]. Another battery recycler, Chemetall, will recover most valuable materials from batteries [14]. Plastics and graphite, however, are not recovered. The process recovers lithium in the form of LiOH after the cathode material undergoes leaching and extraction with hydrochloric or sulfuric acid, crystallization and ion exchange, and, finally, electrodialysis.

The Eco-Bat process is a direct recycling process and recovers additional components of lithium ion batteries for direct reuse, most significantly the lithium-salt cathode material [12]. Relithiation of the cathode material may require some virgin lithium carbonate but the active material structure is maintained. The electrolyte solvent and salts, the carbon anode, and metal parts are also recovered. Like the Toxco process, the Eco-Bat process is low-temperature and consumes minimal energy.

Depending on the process, recycling can have a minimal or significant overall effect on the life cycle impacts of lithium ion batteries. Figure 2 displays the major steps in the battery life cycle, incorporating the first two steps in Figure 1. If the recycling process is smelting, only steps with blue squares will be obviated. An intermediate process (Toxco/Recupyl) will displace those steps leading up to and indicated with an orange circle. Purple triangles correspond to direct recycling and indicate that the marked step and those that precede it are unnecessary. The yellow oval highlights the overall steps that direct recycling precludes, which is nearly all steps but the stage two battery assembly.

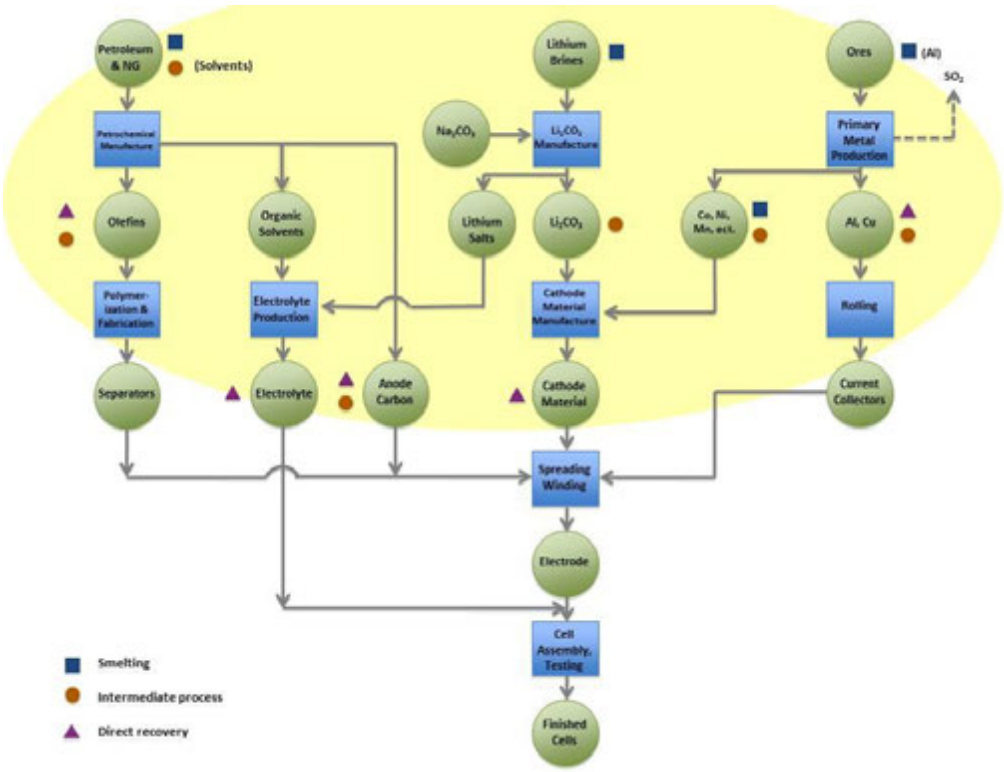

Figure 2. Schematic Flow Chart for Production of Lithium-Ion Cell Materials. Symbols represent stage to which different recycling processes return materials. Shaded oval shows process steps avoided by direct recycling [15].

The preceding discussion describes closed-loop recycling, where recycled materials route back to a point within the battery's life cycle. One interesting question that LCA can address is how the recovery of products that may be re-used, but not directly in a battery in an open-loop recycling scheme, could be attributed to the life cycle of a battery. In a sense, these products, such as iron, copper, nickel, mixed plastics, and mixed metal oxides, are co-products of the battery life cycle. In other product systems, such as biofuels, co-products are treated as displacing conventionally-made products and the avoided energy consumption and emissions resulting from producing these products (like electricity and animal feed) are allocated to the main product (the biofuel) as a benefit, reducing its life cycle energy consumption and emissions.

Contribution of Lithium Ion Batteries to the Life Cycle Energy of PHEVs

We have used the GREET model [16,17] to examine the contribution of a lithium ion battery to the life cycle energy consumption of a plug-in hybrid electric-20 (PHEV-20) vehicle with a lifetime of 257,500 km and no battery replacement. We describe vehicle components other than the battery elsewhere [16] and note that the impacts of the battery will likely increase approximately linearly with all electric range.

Figure 3 displays the results of this analysis, which show that overall, the battery CTG energy consumption is approximately 1% of the total vehicle cycle, which includes the vehicle cycle of the battery, car components other than the battery, and the pump-to-wheels and well-to-pump stages of the fuel cycle.

Figure 3 also shows a breakout of the battery CTG energy by stage. Stage two is 2.4% of the total CTG energy in this analysis.

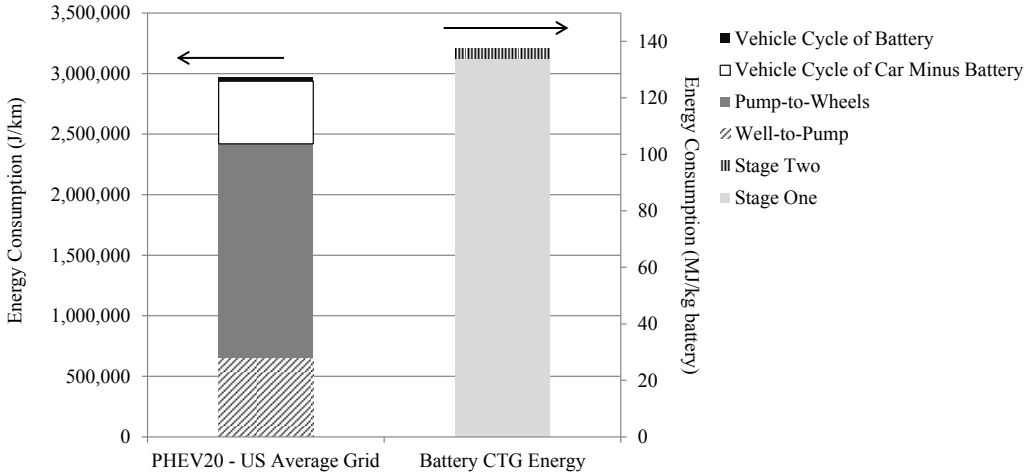

Figure 3. Life cycle energy of a PHEV20 and battery CTG energy

Conclusions

LCA is a useful tool to examine the life cycle of batteries and has essentially demonstrated that stage two is not a primary energy consumer in lithium batteries' life cycles. Further, LCA can capture the impact of recycling on batteries' life cycle, whether the effects are felt only in stage one or in both stages one and two. It is also possible to extend the analysis to open-loop recycling wherein the benefits of battery recycling would be felt in other sectors with the benefits assigned back to the battery. Certainly battery assembly (stage two), the preceding supply chain (stage one), and recycling (stage five) are subject to changes in technology that LCA practitioners must monitor, accounting for technology advancements and shifts in future analyses.

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