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Status of life cycle inventories for batteries

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A R T I C L E I N F O

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This study reviews existing life-cycle inventory (LCI) results for cradle-to-gate (*ctg*) environmental assessments of lead-acid (PbA), nickel–cadmium (NiCd), nickel-metal hydride (NiMH), sodium-sulfur (Na/S), and lithium-ion (Li-ion) batteries. LCI data are evaluated for the two stages of cradle-to-gate performance: battery material production and component fabrication and assembly into purchase ready batteries. Using existing production data on battery constituent materials, overall battery material production values were calculated and contrasted with published values for the five battery technologies. The comparison reveals a more prevalent absence of material production data for lithium ion batteries, though such data are also missing or dated for a few important constituent materials in nickel metal hydride, nickel cadmium, and sodium sulfur batteries (mischmetal hydrides, cadmium, β-alumina). Despite the overall availability of material production data for lead acid batteries, updated results for lead and lead peroxide are also needed. On the other hand, LCI data for the commodity materials common to most batteries (steel, aluminum, plastics) are up to date and of high quality, though there is a need for comparable quality data for copper. Further, there is an almost total absence of published LCI data on recycled battery materials, an unfortunate state of affairs given the potential benefit of battery recycling. Although battery manufacturing processes have occasionally been well described, detailed quantitative information on energy and material flows are missing. For each battery, a comparison of battery material production with its manufacturing and assembly counterpart is discussed. Combustion and process emissions for battery production have also been included in our assessment. In cases where emissions were not reported in the original literature, we estimated them using fuels data if reported. Whether on a per kilogram or per watt-hour capacity basis, lead-acid batteries have the lowest cradle-to-gate production energy, and fewest carbon dioxide and criteria pollutant emissions. The other batteries have higher values in all three categories.

1. Introduction

Concerns over the economic and energy security implications of US dependence on foreign oil, in addition to increasing apprehension about greenhouse gas (GHG) emissions and their impact on climate change, has spurred a renewed interest in improving the nation's energy efficiency. To address these concerns, a number of initiatives and policies have been established, including the Renewable Portfolio Standards enacted by many states to address the "greening" of their electricity grids. Another example involves recent actions taken by both the government and the auto industry to develop affordable, advanced battery technologies for vehicle traction. When used for partially and fully electrified vehicles, the advantages of such batteries would be reduced oil consumption and carbon dioxide (CO_2) emissions. In addition, whether used as new or after use in vehicles, such batteries could supply a storage option to the electrical grid for renewable energy generated during off-peak periods. Battery technologies required to provide traction in vehicles, with practical driving ranges between rechargings, represent a significant departure in material composition from the lead-acid (PbA) batteries found in conventional vehicles. Whether used for vehicles, the grid, or both, the question at hand is the level of environmental benefit that could potentially be provided by these batteries, considering their material differences and the sheer number that would be required. life-cycle inventory (LCI) analysis is the method of choice for answering this question.

A number of life-cycle studies have been conducted on rechargeable batteries, though usually in the context of their applications. As electrification of cars and trucks is viewed as a significant step toward reducing energy consumption in the transportation sector, a number of studies have been conducted on traction batteries [1–8] ranging from lead acid to lithium ion. Because the production of batteries is generally energy intensive, life-cycle energy and combustion emissions for them when used in vehicles

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Nomenclature

$\{B\}_k$	battery environmental burden vector for life-cycle stage k
$\{b_j\}$	environmental burden vector for the production of material j
C_j	production efficiency of material j
ctg	cradle to gate life-cycle stage
E_{ctg}	cradle to gate energy for a battery
E_{mp}	material production energy for a battery
E_{mnf}	manufacturing energy for a battery
G	graphite anode
GHG	greenhouse gas
GREET	greenhouse gases, regulated emission, and energy use in transportation
LCA	life-cycle assessment
LCI	life-cycle inventory
LFP	lithium iron phosphate cathode
LMO	lithium manganese oxide cathode
m_j	mass of material j
mnf	manufacturing life-cycle stage
mp	material production life-cycle stage
NCA	nickel, cobalt, aluminum oxide cathode
NCM	nickel, cobalt, manganese oxide cathode
PE_j	production energy of material j
PE	Polyethylene
PP	polypropylene
TiO	titanium oxide anode

have been of particular interest due to their potential to displace all or part of the energy and emissions from conventional vehicles. Further, some researchers, recognizing battery potential for grid electricity storage, have developed life-cycle data for application to photovoltaic (PV) energy storage [9,10].

Given that advanced battery technologies are based on comparatively valuable constituent materials, e.g. cobalt, metal hydrides and others, an interest in battery recycling has also developed. For example, companies such as UMICORE, TOXCO, OnTo, and others are major developers of battery recycling technology. UMICORE and TOXCO currently have commercially viable operations for recycling battery materials. The recycling of battery materials can significantly reduce the material production component of the life-cycle of battery manufacturing. Though some research has been conducted on the impact of recycling on battery life-cycles [6,11,12], much is still unknown. Furthermore, in some cases such as lithium ion batteries, more needs to be determined on the material production of some virgin materials.

The purpose of this report is to review and evaluate published life-cycle inventory data on the cradle to gate (*ctg*) production energy and combustion and process emissions for batteries. This includes the life-cycle stages of battery materials production and subsequent battery manufacturing, which takes into account both component production and battery assembly. The report covers both what is known about battery life-cycles, as well as establishes life-cycle data needs for better environmental evaluations. Battery material production values calculated from available constituent material production data are compared to literature values. The material production stage's share of the *ctg* battery production energy was also estimated. Also discussed is battery manufacturing. Further, carbon dioxide and criteria pollutant emissions either taken from the literature or calculated from published fuels data are compared among the batteries. The battery technologies considered are lead acid (PbA), sodium-sulfur (Na/S), nickel cadmium (NiCd), nickel metal hydride (NiMH), and lithium ion (Li-ion) battery systems.

2. Methods and metrics

2.1. Assessment method

The preferred approach to environmental evaluations of product systems is life-cycle analysis (LCA) [13–15]. The LCA is a method that provides a system-wide perspective of a product or service — one that considers all stages of the life-cycle, including material production, system manufacture and assembly, service provision, maintenance and repair, and end-of-life processes.

The evaluation of battery life-cycle studies reviewed herein is based on the process life-cycle assessment framework. More specifically, the evaluation places a high value on studies where detailed process-specific data are presented; ideally, those where unit process flows have been either provided or referenced. Quantifying material and energy flows in a product life-cycle is an activity of the inventory stage of LCA, often referred to as life-cycle inventory (LCI) analysis. Ideally, the material and energy life-cycle data gathered in an LCI are fully speciated. By this we mean that the purchased (or direct) energy units (liter [L], kilowatt-hour [kW h], cubic meter [m^3], and kilogram [kg]) and specific material consumptions (kilograms) are given. Such detail helps identify opportunities for product or process improvement and fuel substitutions — an important objective of LCA.

Unfortunately, for competitive or proprietary reasons, detailed and quantitative product assembly information about processes or products are often not provided by manufacturers, whether for batteries or other products. In the absence of such detail, aggregated energy and materials information must suffice. However, for the reasons just discussed, such information must be considered of lower quality. Alternatively, some authors employ economic input/output (EIO) energy data. We have not included such data in our assessment, since such analyses tend to have a sector wide dimension and are generally devoid of process detail.

2.2. System boundary

A representation of the flows required to characterize a unit process is depicted in Fig. 1. Typically, numerous such processes are required to manufacture most products. For example, in making a PbA battery, unit processes are needed for the production of lead, lead compounds, acid, battery cases, poles, separators, copper, and other components, as well as one or more processes for putting it all together into a purchase-ready product. Further, the production of materials also requires a number of unit processes. For example, the unit processes required to produce virgin lead are mining, beneficiation, ore preparation, smelting, and refining.

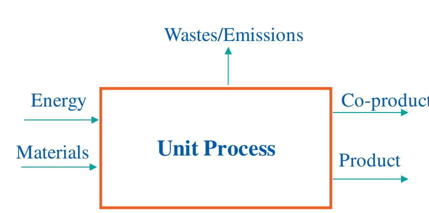

Fig. 1. Generalized unit process.