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A Review of Battery Life-Cycle Analysis: State of Knowledge and Critical Needs

Energy Systems Division

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A REVIEW OF BATTERY LIFE-CYCLE ANALYSIS:
STATE OF KNOWLEDGE AND CRITICAL NEEDS

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ABSTRACT

A literature review and evaluation has been conducted on cradle-to-gate life-cycle inventory studies of lead-acid, nickel-cadmium, nickel-metal hydride, sodium-sulfur, and lithium-ion battery technologies. Data were sought that represent the production of battery constituent materials and battery manufacture and assembly. Life-cycle production data for many battery materials are available and usable, though some need updating. For the remaining battery materials, life-cycle data either are nonexistent or, in some cases, in need of updating. Although battery manufacturing processes have occasionally been well described, detailed quantitative information on energy and material flows is missing. For all but the lithium-ion batteries, enough constituent material production energy data are available to approximate material production energies for the batteries, though improved input data for some materials are needed. Due to the potential benefit of battery recycling and a scarcity of associated data, there is a critical need for life-cycle data on battery material recycling. Either on a per kilogram or per watt-hour capacity basis, lead-acid batteries have the lowest production energy, carbon dioxide emissions, and criteria pollutant emissions. Some process-related emissions are also reviewed in this report.

1 INTRODUCTION

Concerns over the economic and energy security implications of the U.S. 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 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, when used for the grid, such batteries could supply a storage option for renewable energy generated during off-peak periods. However, the 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.

A significant increase in the use of rechargeable batteries has occurred during the last few decades. Until now, this increase has been driven mostly by the consumer electronics marketplace for applications in cell phones, laptop computers, power tools, toys, energy storage for remote sensing devices, and, more recently, hybrid-electric vehicles. The type of rechargeable batteries employed for many of these applications was initially nickel-cadmium (NiCd) batteries, which have been mostly replaced by nickel-metal hydride (NiMH) systems, which in turn are now being displaced by lithium-ion (Li-ion) batteries. Because of the value of some of the constituent elements in these batteries, considerable effort has been devoted to the recycling of rechargeable batteries. 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.

While significant advances are being made in the recycling of rechargeable batteries, much has yet to be quantified on the actual environmental performance of those processes, whether the output product is intended for batteries or other applications. Further, it turns out that much also needs to be elucidated in the environmental performance of advanced battery manufacturing using virgin materials. Indeed, it is the latter performance that is the logical basis of comparison for battery recycling.

The preferred approach to environmental evaluations of product systems is life-cycle analysis (LCA) (ISO 14040, 14041, and 14042) (ISO 1997, 1998, and 2000). 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. Though generally the objective of an LCA is a cradle-to-grave evaluation, in this study the focus is on cradle-to-gate (CTG) assessments.

The purpose of this report is to review the literature on battery life-cycle assessments with a focus on CTG energy and GHG and criteria emissions. This includes battery manufacturing and as the production of materials that make up batteries. Our survey covers both what is known about battery life cycles, as well as what needs to be established for better environmental evaluations. The battery technologies considered are PbA, sodium-sulfur (Na/S), NiCd, NiMH, and Li-ion battery systems. These batteries are used for numerous applications, including computers, cell phones, vehicles, power tools, and grid energy storage, among others. Though our survey has identified other battery technologies, we do not address them in this report, as it was determined that their potential for significant market penetration is low at this time.

2 EVALUATION CRITERIA

The evaluation of battery life-cycle studies reviewed herein is based on a 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. A representation of the flows required to characterize a unit process is depicted in Figure 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, 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 lead are mining, beneficiation, ore preparation, smelting, and refining.

FIGURE 1 Generalized Unit Process

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 [kWh], cubic meter [m^3], and kilogram [kg]) and specific material consumptions (kilograms) are given. Studies that provide greater detail instill more confidence in the results and generally present a more complete picture of the product and its manufacturing processes, thereby enabling better environmental assessments. The advantage of additional detail helps to identify opportunities for product or process improvement — an important objective of LCA. Figure 2 depicts the full life cycle of products; in our case, those products are batteries. As our interest centers on CTG assessments, the stages covered for our analysis are battery materials production, battery manufacturing, and recycling. Although batteries can be used for numerous applications, it is not our intention to characterize how they are used, but rather to address the requirements necessary to bring them to the purchase-ready state. This is the reason for the CTG focus. Because new batteries can in principle be made from recycled materials, battery recycling is also considered.

FIGURE 2 Boundaries Assumed for the Cradle-to-Gate Study Evaluation

The system boundary includes all relevant activities at the battery manufacturer's facility, plus all pertinent activities associated with suppliers (Tier 1, 2, etc.). In these analyses, all energies, emissions (where available), and constituent materials associated with battery production are tracked, including ores extracted from the earth and, if available, materials derived from the recycling pool. Including the latter is becoming increasingly desirable given the long-term outlook on the availability of certain elements used in batteries, as well as the national objective of reducing product production energy and associated carbon emissions.

In this discussion, the following terminology is used. *Material production* refers to winning raw materials from earth or a recycling stream and refining them into usable basic (commodity) materials purchased by a manufacturer to produce battery components. This includes bars of nickel (Ni), cobalt (Co), and lead (Pb); sheets of aluminum (Al), steel, and copper (Cu); and amounts of graphite, Li_2CO_3, glass fiber mattes, plastic pellets, and so forth. *Battery manufacturing* represents all processes needed to convert these basic commodity materials into battery components, such as anodes, metallic foams, cathodes, and electrolytes, and to assemble them into a purchase-ready product. In short, this stage addresses the production of structures from materials. *CTG_battery production* denotes the sum of both these life-cycle stages. As such, it represents the environmental burdens incurred to produce a purchase-ready battery.

The LCI for the production of batteries can be written as:

$$\{B\}_{ctg} = \{B\}_{mp} + \{B\}_{mnf}, \tag{1}$$

where ctg denotes cradle-to-gate, mp stands for material production, and mnf indicates manufacturing. $\{B\}$ is a vector quantity comprised of a number of components "B_i", with each representing a particular environmental burden for the battery. Examples of such burdens include the emissions of CO_2 and the consumption of iron ore, natural gas, and water, as well as many others. Because products are usually composed of a number "n" of materials "j" in amounts of

"m_j", the environmental burdens associated with the production of these materials must be quantified. For example, PbA batteries contain lead, lead peroxides, lead sulfate, sulfuric acid, water, plastics, and glass. Hence, the burden vector for material production of a battery is, in matrix notation:

$$\{B\}_{mp} = [B] * \{m\}, \tag{2}$$

where the components of the matrix [B], B_{ji}, represent the burden "i" per unit of material "j", and $\{m\}$ is the mass vector of material components "m_j" for the battery. Each row of [B] is a vector of burdens for material "j", which when viewed on its own is written as $\{b\}_j$ with components b_i. In short, [B] is a stack of row vectors for materials that comprise a product of interest — in this case, a battery.

Some further elaboration is required on the actual meaning of the various B_{ji}. In general, each component of [B] is the sum of burdens "i" from the preceding process steps required to make a unit of "j". Depending on the substance, the units of the components of [B] include mass, volume, kilowatt-hours, and others, where all are based on a unit of "j". In some cases, a component can be a rolled-up quantity, such as life-cycle energy. In this case, it would be a linear combination of other elements of B_{ji} for a given "j" (i.e., $\{b\}_j$), where each of the appropriate "i" values used (fuels in this case) has been converted to a common energy unit and modified to account for the energy of fuel production. For notational simplicity, we denote this component of [B], representing the primary material production energy for a kilogram of each material "j", as PE_j. Similar consolidations can be done for other components of $\{b\}_j$, such as life-cycle or CTG CO_2 emissions.

An expression similar to equation (2) for representing $\{B\}_{mnf}$ is employed, except in this case the components of $\{m\}$ represent battery components or structures (e.g., cathodes, anodes, etc.) and not materials per se. Using the notation of E_{mp} to denote the total material production energy for making the materials in the battery, it follows that the CTG primary production energy for making the battery, a component of $\{B\}_{ctg}$, is:

$$E_{ctg} = E_{mp} + E_{mnf} \tag{3}$$

Similar expressions to equation (3) for other rollup quantities can also be written.

As mentioned above, detailed process information and flow are most desirable for LCI efforts. Unfortunately, for competitive or proprietary reasons, detailed product assembly information about processes or products is often not provided by manufacturers, whether for batteries or other products. If such detail is not available, then rolled-up energy and materials information must suffice. However, for the reasons mentioned earlier, such information is of lower quality. In the absence of process life-cycle data, some authors employ economic input/output (EIO) energy data. We have not included such data in this review, since the associated analyses are generally devoid of process detail. Such detail, typically included in traditional or process chain LCA, permits the identification of product environmental improvement opportunities — a core objective of LCA.

Table 1 lists some key properties of the battery technologies covered herein. Details on the composition and chemistry of each battery technology are given in the appropriate section of this report. For each battery technology, the material production, battery manufacturing, and CTG production energy, on the basis of per kilogram of battery, have been extracted from the literature and are listed in Table 2. (See Appendix A, Table A-1, for values on a megajoule [MJ]/watt-hour [Wh] basis.) Because these energy values mostly are unspeciated, we must make judgment calls regarding the actual fuels used for various processes (if known) to compute GHG and other emissions. In those few cases where such detail is available, GHG emissions have been calculated by using GREET 1.8. Emissions are discussed in a separate section. In the following sections, we address in detail the status and quality of life-cycle data for material production, battery manufacture, and their sum, i.e. $\{B\}_{mp}$, $\{B\}_{mnf}$, and $\{B\}_{ctg}$.

TABLE 1 Key Properties of Various Battery Technologies

Technology	Application[a]	Specific Energy (Wh/kg)	Open-Circuit Voltage (V)	Cycle Life	Energy Efficiency (%)
PbA	EV	35–50	2.1	500–1,000	80+
	PV	20–32		700[b]–1,500[c]	70–84
NiCd	EV	40–60	1.3	800	75
	PV	22–30		1,200[b]–5,500[c]	65–85
NiMH	EV	75–95	1.25–1.35	750–1,200	70
	PV	35–55		1,000[b]–2,900[c]	65–85
Li-ion	EV	75	2.5		
	PV	80–120		6,000[b]–8,500[c]	85–95
Na/S	EV				
	PV	103–116		4,700[b]–7,200[c]	75–83

Sources: Rantik 1999 and Rydh 2005.
[a] EV = electric vehicle; PV = photovoltaic energy.
[b] Cycle life at 80% depth of discharge.
[c] Cycle life at 33% depth of discharge.

TABLE 2 Cradle-to-Gate Life-Cycle Energy (MJ/kg) Results for Five Battery Systems[a]

Battery	Note	E_{mp}	E_{rcycl}	E_{mnf}	E_{ctg}	Reference
NiMH		108	19.6	8.1	119	Ishihara et al. (website)
					230	Ishihara et al. 1999
	AB$_2$				246	Gaines et al. 2002
					195	Gaines et al. 2002
	AB$_5$				263	Gaines et al. 2002
		57				Gaines and Singh 1995
		54–102	21–40[b]	74–139	128–241	Rydh and Sanden 2005
				14.6		Rantik 1999
		86.5		105	191.5	GREET 2.7
PbA		25.1	8.4	11.3	36.4	Ishihara et al. (website)
				77		Ishihara et al. 1999
		24.7				Gaines and Singh 1995
		15–25	9.0–14.0[b]	8.4–13	23.4–38	Rydh and Sanden 2005
				16.6		Rantik 1999
		16.8		6.7	23.5	Kertes 1996
		17.3	Included	8.81	26.1	Hittman Associates 1980
NiCd		102.8				Gaines and Singh 1995
		44.0		53.9	97.9	Kertes 1996
		44–60	22–30[b]	46–63	90–123	Rydh and Sanden 2005
Na/S		59.9				Gaines and Singh 1995
		179		56	235	Hittman Associates 1980
		82–93	30–34[b]	62–70	144–163	Rydh and Sanden 2005
Li-ion	NCA-G	93.3	4.8	32	125.3	Ishihara et al. (website)
	LMO-G	113	3.6	30	143	Ishihara et al. (website)
	NCA-G	53–80	25–37[b]	96–144	149-224	Rydh and Sanden 2005
		112.9		91.5	204.4	GREET 2.7
	NCA-G				222[c]	Umicore Slide/Virgin Materials
	NCA-G				62.9[c]	Umicore Slide/Recycled Materials

[a] See Section 3.1.4 for Li-ion nomenclature; E_{rcycl} denotes energy to recycle the battery; see Table A-1 for megajoule/watt-hour values.
[b] Reported as material production energy using recycled materials.
[c] These values are per cell.

3 ENERGY ANALYSIS

3.1 MATERIALS PRODUCTION

This section covers in detail the material composition and material production energy of the five battery technologies named above. An overview of the production of many of the materials in these batteries has been presented by Gaines et al. (2002) and Gaines and Singh (1995). Also, a good discussion of the processes required to make battery materials can be found in the EVTECA report (1998), which includes a few flow diagrams and some rolled-up data. This report encompasses those and more recent results.

There is uncertainty about some of the material production energies (PE$_j$) listed in the following tables. In these cases, it is not clear whether the reported energies are aggregated direct energy consumption or life-cycle values, which include fuel production energies. These values have been taken from references that do not specify whether fuel production energies for fossil fuels are included. Further, because those fossil fuel consumptions are reported in energy units (megajoule and Btu), it is difficult to infer whether they are direct or life-cycle values. Uncertainties such as this highlight the value of reporting energy consumptions in purchased energy units, such as cubic meters, kilowatt-hours, liters, tons, gallons, and so forth, from which life-cycle values are readily computed.

3.1.1 Lead-Acid Batteries

The PbA batteries have been in use for more than a century, primarily as an automotive starter battery. During that time, they have undergone steady improvements in efficiency, durability, and lifetime. The chemistry remains unchanged. The main components of the battery are: a cathode comprised of lead peroxide on a lead lattice for support; an anode made of sponge lead, also on a lead lattice; an electrolyte of water and sulfuric acid; fiberglass matte (with some polymeric binders) separators that keep the anode and cathode apart; and a containment case, typically made of polypropylene. During discharge, lead at the cathode is reduced (PbO$_2 \rightarrow$ PbSO$_4$), whereas at the anode it is oxidized (Pb $\rightarrow$ PbSO$_4$). During recharging, these two reactions go in the opposite direction. The composition of a typical PbA battery is given in Table 3.

TABLE 3 Composition for a Representative Lead-Acid Battery

Item	Percentage[a]
Lead	25
Lead oxides	35
Polypropylene	10
Sulfuric acid	10
Water	16
Glass	2
Antimony	1

[a] Estimated based on the Materials Safety Data Sheet and other sources.

A typical new PbA battery contains 60% to 80% recycled lead and plastic (Battery Council International 2010). Antimony (or calcium) is alloyed with the lead to suppress electrolysis of water during recharging. This innovation has eliminated the need to periodically add make-up water to batteries.

Ample LCI data are available on the production of lead, polypropylene, and sulfuric acid, which are the primary ingredients (by mass) in a PbA battery. A listing of some of that LCI data is given in Table 4, along with an assessment of their quality in terms of energy and process detail.

The data listed in Table 4 are a few of the possible values and sources of the production energy for PbA battery materials, PE_j. However, the sources listed are considered more favorable studies in that they provide at least some process detail and associated energies. The Hittman report (Hittman Associates 1980) provides considerable detail for energy only. Unfortunately, however, those data are 30 years old, and much has changed since that time. While energy efficiency initiatives on the part of industry have reduced production energies, the addition of emission control devices, on the other hand, has increased them. The net is uncertain. Although the Hittman report lists only primary energies (coal, petroleum, natural gas, and electricity) for each process in energy terms (BTUs), one can nevertheless estimate actual fuel uses (liters of gasoline and fuel oil, cubic meters of natural gas, etc.) from those listings by using process judgment on the likely fuels and the well-known low heat values and production efficiencies for them. Even though it is not clear whether they included fuel production energies, the uncertainty is only about 10%. The same applies to some of the production energy data cited in EVTECA (1998) for battery materials.

TABLE 4 Cradle-to-Gate Production Energy Values and an Assessment of Data Detail for Lead-Acid Battery Materials

Material		PE_j (MJ/kg)	Energy Detailed[a]	Process Detailed[a]	Reference
Pb	Virgin	31.2	Y	Y	Hittman Associates 1980
	Virgin	28.7	Y	Min	Boustead and Hancock 1979
	Virgin	22.3	Y	Min	GREET 2.7
	Virgin	27.2	Y	Y	EVTECA 1998
Pb → PbO		12.7	Y	Y	Hittman Associates 1980
Pb	Recycled	11.2	Y	Y	Hittman Associates 1980
	Recycled	4.2	Y	Min	GREET 2.7
	Recycled	7.2	N	N	Boustead and Hancock 1979
	Recycled	5.3	Y	Y	EVTECA 1998
Polypropylene					
	Virgin	75.5	Y	Y	NREL/LCI Database (NREL 2010)
	Virgin	73.4	Y	Y	Plastics Europe 2010
	Recycled	15.1	N	N	EVTECA 1998
Sulfuric acid		0.042	Y	Y	Hittman Associates 1980
Glass		20	Y	Min	GREET 2.7
Glass fiber		25.9	Y	Y	EVTECA 1998

[a] Y = yes; N = no; Min = minimal.

For plastics, the eco-profiles developed by Plastics Europe and the U.S. Life-Cycle Inventory (LCI) database provide not only very detailed purchased fuel data, but also numerous other flows to air and water. Further, those data sets are comparatively recent.

As shown in Table 4, the PE_j values for lead are reasonably consistent, and two references provide substantial process detail. Also evident in the table is that the PE_j for recycled lead is on average about a third of that for making lead from virgin resources. Energy data for polypropylene production and associated processes are state-of-the-art. Sulfuric acid production energy is quite small and contributes little to the total material production energy of PbA batteries. Employing the composition and production energy data for virgin materials given in Tables 3 and 4, E_{mp} is estimated to be 28 MJ/kg of battery. Relative to the values given in Table 2, this value is on the high side. As shown later, this changes with the use of recycled materials.

3.1.2 Nickel-Cadmium Batteries

The NiCd batteries experienced a considerable boom in popularity during the last quarter of the twentieth century, primarily due to greater demand for battery-powered devices (phones, toys, hand tools, etc). One of the advantages of these batteries is that they can sustain high discharge rates without adversely affecting battery capacity. However, they do suffer from a memory effect, since they lose capacity if recharged before completely discharged. The components of the battery are a cathode comprised of nickel hydroxy-oxide, an anode made of metallic cadmium, and an electrolyte of potassium hydroxide (KOH). During discharge, Ni is reduced (NiOOH $\rightarrow$ Ni(OH)$_2$) at the cathode, and cadmium (Cd) is oxidized (Cd $\rightarrow$ Cd(OH)$_2$) at the anode. Typically, the cathode and anode are rolled up into a "jelly roll" configuration and placed in a steel case, though a prismatic battery configuration is also available. The cathode and anode are separated by a porous polymeric separator strip (three thin layers that consist of nylon/polypropylene/nylon), with the electrolyte free to diffuse through it. This configuration is used for wettability purposes. The typical composition of NiCd batteries is shown in Table 5.

TABLE 5 Materials in an Automotive Nickel-Cadmium Battery

Item	Percentage[a]
Cd	25
Ni powder	20
Ni(OH)$_2$	17
KOH	5
Plastics	3
Steel and copper	16
Water	12
Other	2

[a] Source: Gaines and Singh 1995.

The PE_j values for the constituent materials of NiCd batteries are listed in Table 5. Unfortunately, there is very limited information on Cd production, the most reliable of which appears to be that published by Boustead et al. (1999) (see Table 6). One other PE_j for Cd is listed in Table 6, but it is considered less reliable due to ambiguity over co-product allocation procedures (Gaines and Singh 1995). That value is based 1976 data for that industry's Cd output and associated direct energy consumption (Llewellyn 1993). At this time, the Boustead value, which is based on an elemental mass allocation procedure (Boustead et al. 1999), is considered the most reliable.

TABLE 6 Life-Cycle Energy Values, Assessment, and Sources for Both Nickel-Cadmium and Nickel-Metal Hydride Battery Materials

Material		PE_j (MJ/kg)	Energy Detailed[a]	Process Detailed[a]	Reference
Cd	Virgin	70	N	N	Boustead et al. 1999
Cd	Virgin	193	N	N	Gaines and Singh 1995
Ni	Ore → Ni	186	N	N	Gaines et al. 2002
Ni	Ore → Ni	122	N	Y	EVTECA 1998
Ni	Ore → Ni	167	Y	Y	Hittman Associates 1980
Ni	Ore → Ni	224	Y	Y	Nickel Institute 2007
Ni	Ore → Ni	148	Y	Y	GREET 2.7
Ni – recycled		37	Min	Min	GREET 2.7
Ore → Ni(OH)$_2$		193	Y	Y	Hittman Associates 1980
Ni → Ni(OH)$_2$		33	Y	Min	GREET 2.7
Ni → Ni(OH)$_2$		76.7	N	N	Gaines et al. 1995
Ni → Ni(OH)$_2$		90.6	Y	Y	Hittman Associates 1980
KOH		38.2	Y	Y	Hittman Associates 1980
"		10.8	N	N	EVTECA 1998
Mischmetal		50.4 kwh.kg	Y	Y	Ishihara et al.1999
Steel		37.2	Y	Y	GREET 2.7
Nylon		120	Y	Y	Plastics Europe 2010
Polypropylene		80	Y	Y	Plastics Europe 2010

[a] Y = yes; N = no; Min = minimal.

On the other hand, a number of production energy values are available on the production of nickel. The PE_j values and associated references are given in Table 6. The Nickel Institute has conducted a comprehensive LCI on the CTG production of Ni, nickel oxide (NiO), and ferronickel. Their study has the scope, depth, and transparency of a well-conducted LCI for a material, thereby making it comparable to other exemplary studies, such as those done by Plastics Europe and the Aluminum Association (1998). All relevant processes have been included, such as mining, beneficiation, ore preparation, and refining. Details are available on their website. Other constituent materials of NiCd batteries, such as nylon and steel, also have good LCI data that are publicly available.

With the exception of Cd, the PE_j values given in the table are quite reliable. The values come from a set of references that collectively provides adequate production energy values and process details from a life-cycle perspective. From those PE_j values, and assuming a composition of (Cd, Ni, Ni(OH)$_2$, KOH, nylon, steel)% = (25,20,17,5,3,16)%, the E_{mp} for NiCd batteries is estimated to be about 98 MJ/kg, which is at the high end of the ranges shown in Table 2. Incidentally, one expects a range of E_{mp} values for these and other batteries. After all, E_{mp} values are dependent on battery material composition, which in turn is dependent on the application. For example, in contrast to the value just given, we estimate an E_{mp} equal to 84.2 MJ/kg for a small

consumer product battery with the composition of (16, 21, 8, 4, 4, 39)% (Rydh and Karlstrom 2002).

3.1.3 Nickel-Metal Hydride Batteries

These batteries have become very popular, especially for power tools and hybrid vehicle applications. As seen in Table 1, these batteries have a better specific energy than NiCd batteries, and they do not suffer from a memory effect. The NiMH batteries have displaced NiCd batteries in many applications, especially in the hand-held power tools market. The components of the batteries are: a cathode comprised of nickel hydroxyl oxide, an anode of mischmetal (Me) hydrides, an electrolyte of KOH, and a separator of a porous polypropylene membrane. During discharge, the reaction at the cathode is the same as that for NiCd batteries; that is, the Ni is reduced ($NiOOH \rightarrow Ni(OH)_2$) and the mischmetal is oxidized ($MH \rightarrow M$) at the anode. Mischmetals are metals from the lanthanide series, or rare earths, including metals from lanthanum (atomic number = 57) to luterium (71), which in the context of batteries are referred to the AB_5 type. Even though it is not a lanthanide, ytterium (39) is also included in this group. Another group of metals used for NiMH anodes is the AB_2 type, which includes titanium (Ti), zirconium (Zr), Ni, and vanadium (V).

A typical composition of an NiMH battery is given in Table 7 for both the AB_2 and AB_5 batteries. However, compositions can vary widely depending on the application. Consistent with their respective purposes, high-power batteries tend to have less electrically active material than high-energy batteries, the latter of which are used for traction in electric vehicles.

The PE_j data for this battery's materials are given in Table 6. Unfortunately, there are scant data in the literature on the production of mischmetal. The only reference found for this study was published by Ishihara et al. (1999). As seen in the table, their value, which is a result

TABLE 7 Significant Materials in Representative Nickel-Metal Hydride Batteries

Material	NiMH-AB_2 Percentage	NiMH-AB_5 Percentage
Ni	12	15
Ni(OH)$_2$	12	15
M: Ni, Ti, V, Zr	13	
M: La, Nd, Pr, Ce[a]		8
KOH	3	3
Polypropylene	5	5
Steel	44	44
Other	11	10

[a] FromRantik 1999.

of their "hybrid analysis" (a combination of process LCA and EIO), is very high. If U.S. grid electricity were used to make this metal, the production energy would be 545 MJ/kg. To put this into perspective, the production energy for aluminum is 154 MJ/kg, which is a well-established value and on the high end for metal production.

Overall, most PE_j values for NiMH battery constituent materials are available, except for mischmetal. All the other materials have adequate process fuels data and process information in the references. Based on the PE_j values given in Table 8 and assuming a battery composition of (M, Ni, Ni(OH)$_2$, KOH, PP, steel)% = (10, 12, 12, 3, 5, 44)%, we estimate the E_{mp} for the NiMH battery to be 120 MJ/kg of battery. Compared with the Rydh and Sanden (2005) estimates in Table 2 for the E_{mp} of NiMH batteries, this estimate is on the high side and likely due to the mischmetal production energy. If the mischmetal PE_j were instead a value equivalent to aluminum production, the battery material production energy would be 81 MJ. This value is in much better agreement with the values shown in Table 2. This exercise emphasizes the need for better PE_j values for mischmetal.

3.1.4 Lithium-Ion Batteries

The Li-ion batteries represent a comparatively new technology with superior specific energy and cycle life (see Table 1) and no memory effect. Until recently, the most common application for them has been in electronic products, such as cell phones, hearing aids, computers, and the like. However, they now have begun to displace NiMH batteries in hand-held power tools, and they are considered by many to be the best choice for electric vehicle and plug-in electric vehicle applications. Unlike the batteries discussed thus far, the composition of Li-ion batteries can be quite variable, depending primarily on the composition of the cathode. Table 8 lists Li-ion battery components and constituent materials. The table reveals that a number of cathode and anode materials are available. For examples of specific battery compositions, refer to Gaines and Nelson (2009).

For convenience, we use in two of our tables the following nomenclature (Gaines and Nelson, 2009) to describe some of the Li-ion batteries in terms of their cathode and anode composition. Cathodes are lithium salts of either: 1) a mixture of Ni, Co, and Al oxides (NCA), 2) iron phosphate (LFP), or 3) manganese oxide (LMO). Anodes are either graphite (G) or lithium salt of titanium oxide (TiO).

In Table 8, it should be noted that the percent by weight of electrode materials varies considerably. This is related to battery capacity; as battery capacity increases, the amounts of cathodes and anodes also increase. Because battery operation is a result of chemical reactions, greater capacity means more reactions, which occur in the electro-active materials of the electrodes. For an $LiCoO_2$ cathode and an LiC_6 anode, a representative set of reactions during discharge is: cobalt is reduced (e.g., $CoO_2 \rightarrow LiCoO_2$) at the cathode and $LiC_6 \rightarrow C_6$ at the anode.

TABLE 8 Composition of Lithium-Ion Batteries

Component	Materials	Percentage[a]
Cathodes		15–27
	Li_2CO_3	
	$LiCoO_2$	
	$LiMn_2O_4$	
	$LiNiO_2$	
	$LiFePO_4$	
	$LiCo_{1/3}Ni_{1/3}Mn_{1/3}O_2$	
	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	
Anodes		10–18
	Graphite (LiC_6)	
	$Li_4Ti_5O_{12}$	
Electrolyte		10–16
	Ethylene carbonate	
	Diethyl Carbonate	
	$LiPF_6$	
	$LiBF_4$	
	$LiClO_4$	
Separator	Polypropylene	3–5
Case	Steel	40

[a] Source: Gaines and Nelson 2009.

A summary of PE_j values for materials that comprise Li-ion batteries appears in Table 9. An inspection of the table reveals a considerable dearth of energy information on Li-ion battery materials, whether for anodes, cathodes, or electrolytes. More specifically, PE_j data for Li-ion battery constituent materials, such as $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ and most of the other materials listed in Table 8, are sorely lacking. More information is needed about the reaction pathways from the commodity materials to the materials that make up the battery components listed in Table 8. Because of this, we are unable to estimate the material production energy for these batteries. Nevertheless, some energy data for these batteries are listed in Table 2.

TABLE 9 Life-Cycle Energy Values, Assessment, and Sources for Lithium-Ion Battery Materials[a]

Material	PE_j (MJ/kg)	Energy Detailed[b]	Process Detailed[b]	Reference
Co-precipitation	144	Y	Y	Hittman Associates 1980
Brine → Li_2CO_3	36.6	Y	Y	Author's data
Ore → $LiOH$-H_2O	163	Y	Y	Hittman Associates 1980
Ore → LiCl	220	Y	Y	Hittman Associates 1980
Coke → Graphite	202	N	N	GREET 2.7
Pet. coke → graphite	187	Y	Y	Hittman Associates 1980

[a] Assuming U.S. grid electricity.
[b] Y = yes; N = no.

3.1.5 Sodium-Sulfur Batteries

The Na/S batteries were once thought to be the energy source of choice for electric vehicle applications. Unfortunately, several important issues weighed heavily against them. These batteries require energy to keep them at operating temperature (ca 300°C), and there are safety concerns about molten sodium and highly corrosive sodium polysulphide on-board vehicles. The NaS batteries have good specific energy and cycle life. They are currently being used in Japan for grid energy storage. An example composition for these batteries is given in Table 10. These batteries are distinct from the other batteries that are discussed herein. In this case, the electrodes are liquids and the electrolyte is a solid, whereas for a PbA battery, the electrodes are solids and the electrolyte is liquid. More specifically, for Na/S batteries, the cathode is molten sulfur, the anode is molten sodium, and the electrolyte is solid β-alumina.

Available PEj data for Na/S battery materials are given in Table 11. Unlike its Li-ion counterpart, the Na/S battery is comprised of comparatively common materials for which life-cycle energy data are already available.

TABLE 10 Material Composition of Sodium-Sulfur Batteries[a]

Materials	Percentage[b]
Sulfur	12.5
Sodium	8
β-alumina	10.2
α-alumina	2.3
Steel	12.8
Aluminum	22.7
Graphite	2
Copper	3.4
Polypropylene	8
Glass	4.3
Sand	15.2
Miscellaneous	8.7

[a] Source: Hittman Associates 1980.
[b] ABB.

TABLE 11 Life-Cycle Energy Values, Assessment, and Sources for Sodium-Sulfur Battery Materials[a]

Material	PE_j MJ/kg	Energy Detailed[a]	Process Detailed[a]	Reference
Sodium – Na	165	Y	N	Boustead and Hancock 1979
Sodium – Na	107	Y	Y	Hittman Associates 1980
Sulfur – S	6.7	Y	N	Boustead and Hancock 1979
Sulfur – S	2.3	Y	Y	Hittman Associates 1980
β-alumina	1,189	Y	Y	Hittman Associates 1980
β-alumina	196–635	Min	Min	Gaines and Singh 1995; EVTECA 1998
Aluminum – recycled	45	Y	Y	GREET 2.7
Copper	111	Y	Y	GREET 2.7
Glass	16.3	Y	N	GREET 2.7
Steel				See Table 4
Polypropylene				See Table 4

[a] Y = yes; N = no; Min = minimal.

Overall, material production energy values for Na/S battery constituent materials are quite good, except for the ceramic β-alumina. The PE_j values shown in the table for the ceramic are both high and variable. As such, they are expected to affect estimates of battery E_{mp}. If fact, by employing the PE_j values in the table, including the highest β-alumina value, the battery's E_{mp} is estimated to be 159 MJ/kg. On balance, this is much higher than the values found in Table 2 for the Na/S battery. If instead we use an alternative PE_j value for β-alumina, the average of the other set (Gaines et al. 1995) given in the table, the E_{mp} becomes 80 MJ/kg. This value is in much better accord with the corresponding results given in Table 2. However, because of the magnitude and hence the significance of β-alumina's PE_j value on the E_{mp}, a more reliable value is clearly needed.

3.1.6 Summary of Results

In summary, production energy values are available for many of the commodity materials that make up these five batteries. Although more detailed process descriptions and energy values for some of them are desirable, there is a more pressing need for the following PE_j values: Pb, Cd, mischmetal hydrides, β-alumina, and Li-ion cathode and anode materials.

3.2 BATTERY MANUFACTURING

This section addresses the battery manufacturing stage, which includes the processes and associated energies required to make components and structures from constituent materials and assemble them into batteries. A summary of battery manufacturing energy data from the literature is given in Table 2.

3.2.1 Lead-Acid Batteries

During battery manufacturing, considerable energy is needed to convert the basic battery materials into those required in the battery. In fact, the manufacturing steps include grid manufacturing, paste manufacturing, plate manufacturing, plastic molding, and assembly. The lead oxide listed in Table 2 is first made into a paste, which is electrochemically processed to yield lead peroxide and sponge lead. During paste processing, the products are deposited on lead grids, which also require energy for their production. Of the 31 MJ of energy (E_{ctg}) needed to produce a kilogram of PbA battery, about 9.2 MJ (30%) of it (E_{mnf}) is required to manufacture the battery. Process and energy details for the manufacture of PbA batteries can be found elsewhere (Hittman Associates 1980; Kertes 1996). Rantik (1999) cites a value of E_{mnf} equal to 16.6 MJ/kg and discusses the processes required to manufacture the batteries, including the production of grids, lead oxide, and paste, and the processes of pasting, drying, curing, and formation. Two other values for the E_{mnf} of PbA batteries are 77 MJ/kg (Ishihara et al. 1999) and 12 MJ/kg (Ishihara et al. – web link). We have no explanation for the large difference between his two values. Overall, with the exception of Ishihara's high value, there is a reasonable consistency in the battery manufacturing values given in Table 2.

3.2.2 Nickel-Cadmium Batteries

There is some LCI information on the manufacturing of NiCd batteries. Rydh and Sanden (2005) cite a range of values for E_{mnf}: 46–63 MJ/kg of battery (see Table 2). However, they did not discuss manufacturing processes. The manufacturing processes required to make these batteries are as follows (Kertes 1996): (1) deposit and sinter carbonyl Ni powder in a reduction furnace onto the cathode metal strip to form sponge nickel; (2) impregnate the resulting cathode strip with $Ni(NO_3)_2$ for subsequent conversion to $Ni(OH)_2$; (3) press and roll plastic-bonded (PTFE) Cd with some graphite (to increase porosity and hence conductivity) onto the anode substrate (nickel wire mesh); (4) make the separators (three thin strips of polymer: nylon/polypropylene/nylon); (5) charge the electrodes in excess electrolyte; (6) stack alternating layers of cathode and anode separated by a separator strip; (7) mold the polypropylene case; and (8) add components to the case, including the electrolyte and seal. This set of processes applies to either prismatic or jelly-roll configured batteries. Energy and emissions data are available for only a few of these processes.

3.2.3 Nickel-Metal Hydride Batteries

A summary of life-cycle energy values for NiMH battery manufacturing is given in Table 2, where a number of values of E_{mnf} are recorded. In an online document, Ishihara et al. (website) estimate the E_{mnf} for a 59 Wh/kg battery to be about 8.1 MJ/kg, which is about 9% of the E_{ctg} value (94 MJ/kg of battery), also given there. However, in a separate report (Ishihara et al. 1999) they present a higher value of E_{ctg} (230 MJ/kg). The reason for the large difference in the two values is unknown. Others have also estimated the production energy of NiMH batteries. Based on European data (Kertes 1996), Rydh and Sanden (2005) report E_{mnf} values for NiMH

batteries that range between 74 and 139 MJ/kg of battery. For the latter, no process details have been given. In a proprietary report, Gaines estimates the E_{mnf} to be a little higher.

The manufacturing processes for these batteries include the production of nickel hydroxy-oxide and mischmetal hydrides, preparation of anodes and cathodes, and final assembly. Cathode production for NiMH batteries is virtually identical to that of NiCd batteries. However, the anodes are comprised of metal hydrides, which desorb/absorb hydrogen ions during discharge/recharging, respectively. Details on processes used for commercial preparation of the anodes are not at hand. However, the basic steps (Ananth et al. 2009) are as follows: (1) crush mischmetal hydride, (2) mix with a binder (PTFE) to form a paste, (3) apply to a nickel mesh, and (4) compact and heat treat. The remaining steps are comparable to those for NiCd batteries. The GREET model lists a value of 105 MJ/kg for E_{mnf} of NiMH batteries. Although speciated energy values can be found there, a listing of energies for the unit processes that make up the entire manufacturing chain is not provided.

As seen in Table 2, there is a rather broad range in estimates of E_{mnf} for these batteries. Clearly, from a life-cycle perspective, more consistent estimates of E_{mnf} are needed, including a greater accounting of processes and associated purchased energy.

3.2.4 Lithium-Ion Batteries

The manufacturing of these batteries consists of a number of processes that include: (1) preparation of cathode pastes and cathodes from purchased lithium metal oxides, $LiMe_xO_{y,}$ (Me = Ni, Co, Fe, Mn), binders, aluminum strips, and solvent; (2) preparation of anodes from graphite pastes and copper strips; (3) assembly of anodes and cathodes separated by a separator strip; (4) addition of electrolyte; (5) charging of cells; and (6) final assembly. For more detail, see a discussion by Gaines and Cuenca (2000) on these manufacturing steps. As seen in Table 2, Li-ion E_{mnf} values are quite variable. Indeed, a review of the table reveals a low set of values around 30 MJ/kg and a high set greater than 100 MJ/kg. The low set is based on the work of Ishihara (website), and the high set is from Europe and North America. Ishihara (1996) details the manufacturing processes, including the production of solvent, $LiNiO_2$, $LiPF_6$, indirect effects, and assembly. On the other hand, the sources of the data in the high set provide no process detail.

3.2.5 Sodium-Sulfur Batteries

These batteries are high-temperature systems and require insulation (e.g., hollow glass spheres) to thermally isolate the molten interior from its surroundings. No detailed energy data for the E_{mnf} of these batteries were found. Two sets of manufacturing energy data for Na/S batteries are given in Table 2. The two values are in good accord. Unfortunately, neither reference provides process detail. The Hittman (Hittman Associates 1980) estimate is based on a rule of thumb; that is, 25% of the total production energy is due to E_{mnf}. The other values shown in Table 2 are attributed to Gaines and Singh (1995) by Rydh and Sanden (2005). Unfortunately, Gaines and Singh did not compute a value of E_{mnf} for aNa/S or any other battery.

3.2.6 Summary of Battery Manufacturing Results

In summary, there are life-cycle energy values available for the manufacturing of some of the five battery types discussed herein. Values found in the literature for PbA and NiCd batteries are reasonably consistent within each technology. Values for Na/S batteries are questionable. On the other hand, a broad range of E_{mnf} values are found for Li-ion and NiMH systems. Overall, quantitative energy and material flow data for manufacturing of all these batteries, especially the advanced battery systems, are insufficient to instill confidence in their respective E_{mnf} values and other life-cycle burdens ($\{B\}_{mnf}$).

3.3 RECYCLING OF BATTERIES AND BATTERY MATERIALS

There is a critical need for life-cycle characterizations (process descriptions and flows) of battery material recycling. Indeed, without them, the potential benefit of recycling these materials may be understated. A review of Tables 4, 6, 9 and 11 shows that little information is available on battery material recycling, and the few that are listed represent primarily PbA batteries and not advanced batteries. However, with this limited information, we illustrate below the potential benefit of battery recycling and hence underscore the need for better life-cycle data.

The PbA batteries are highly recycled — some estimate it to be around 95%. Currently, new PbA batteries range from 60% to 80% recycle content (Battery Council International 2010). During recycling, the lead metal (grids and sponge lead), lead peroxide, battery cases, and electrolyte are broken up and separated. The battery case (polypropylene) is washed, pelletized, and sent to battery producers to make new battery cases. The lead metal and peroxides are sent to a smelting furnace to make lead ingots for use in new lead grids. The battery electrolyte, an aqueous sulfuric acid solution, is either neutralized or made into sodium sulfate, which is in turn used for making detergents or other products. As an example of an alternative approach to recycle these batteries, one study (Kertes 1996) reports that in Sweden, after acid removal, the smashed unseparated batteries are fed into a blast furnace to recover only molten lead. The battery plastic is used as fuel in the process.

Using the material production data in Table 4 and assuming that a PbA battery is made up of a 50/50 mix of recycled/virgin lead and 100% recycled plastic (polypropylene), the E_{mp} is calculated to be 17.1 MJ/ kg of battery. This value is in reasonable accord with the E_{mp} range using recycled materials reported by Rydh and Sanden (2005) (see Table 2). Further, our calculated value is considerably lower than 28.4 MJ/kg of battery, if all virgin materials are used. This difference, representing a 40% reduction, highlights the merit of recycling battery materials.

Rantik (1999) cites a value of 4.4 MJ/kg for recycling PbA batteries, a value taken from Kertes (1996). From that value and fuel details, we estimate the PE_j for recycled lead to be about 8.6 MJ/kg. This value is in good accord with the corresponding values in Table 4.

Only one open literature reference was found that cites a value for material production of recycled Ni (see Table 6). In a proprietary report by Gaines et al. (2000), there is another value, which is slightly lower than the value shown in Table 6. Taking the PE_j for recycled Ni from

Table 6 and applying it to all Ni in the battery, including $Ni(OH)_2$, we estimate E_{mp} for the NiCd battery to be 42 MJ/kg, which is half that estimated for the battery made from virgin materials. Depending on the validity of the PE_j for recycled Ni, battery material production energy is significantly reduced, and it could be even lower if Cd and the other constituent materials come from the recycling stream. We also expect it to have the same impact on NiMH battery material production. By applying these same recycled Ni production energy values to the NiMH battery, the E_{mp} is reduced by 36 MJ/kg, relative to that based on virgin materials. This is a significant reduction and, like that for the NiCd battery, could be even larger, if more of this battery's materials came from the recycling stream.

The recycling of advanced batteries, NiCd, NiMH, and Li-ion, is an area in transition. Because of the evolving chemistry for Li-ion batteries and the uncertainties and timing of large-scale deployment of electric vehicles, the recycling industry is finding it challenging to develop profitable recycling pathways. Should the objective be to recover valuable metals in an elemental state or in a form closer to their state in batteries? Currently, the primary motive to recycle NiCd, NiMH, and Li-ion batteries is driven by the valuable metals (Co, Ni, Ti, Cd, Cu) that they contain. The most used approach is pyrometallurgical. Rantik (1999) extracts from the literature (Schluter and Garcia 1996) a value of 4.85 MJ to recycle a kilogram of NiCd batteries. It is purported to yield 0.246 kg and 0.703 kg of Cd and ferronickel, respectively, per kilogram of battery. From his results, we estimate PE_j values for recycled Cd and ferronickel to be 1.26 MJ/kg and 3.6 MJ/kg, respectively. Based on the Kertes (1999) data, Rantik also reports a value of 6.6 MJ/kg to recycle a kilogram of NiMH batteries. From this value, we estimate that the PE_j for recycling ferronickel is 3.7 MJ/kg. The two ferronickel values are in excellent agreement. Unfortunately, ferronickel is not a material that is recycled back into batteries. Instead, it is typically used in making stainless steel. Other materials recovered during the recycling of NiMH batteries include steel/iron, polypropylene, and small amounts of Ni, V, and Cr (Rantik 1999).

Umicore, an advanced materials company, has major operations devoted to battery recycling. Their primary interest is to recover Ni and Co, the latter of which currently commands high returns in the secondary marketplace. Although at this time Umicore does not recover the Li derived from Li-ion batteries, they could do so in the future if lithium prices in the secondary market become attractive. In fact, the battery recycling industry has concerns about the reduction of cobalt use in Li-ion batteries, since reduced yields of Co in that recycling stream could make their processes uneconomical. For Li-ion batteries, Umicore breaks up the batteries, feeds them into a smelting furnace, where metals are recovered, and subsequently sends them to a refiner to get the desired purity of Cu, Fe, Zn, $Ni(OH)_2$, and $CoCl_2$. The $CoCl_2$ is sent to another operation to produce $LiCoO_2$ for use in new batteries. Umicore claims that using recycled Co reduces the production energy for $LiCoO_2$ by 70%. This is a tremendous improvement.

Not all battery recycling operations are pyrometallurgical. TOXCO, Inc., employs a series of steps that include the use of hammer mills, screens, and shaker tables to separate three streams of materials, two of which are sold for their high concentrations of Co, Cu, and Al. They can even recover the Li as Li_2CO_3 at 97% purity and sell it to several industries. Unfortunately, no quantitative energy data are yet available on these processes. Although pyrometallurgy has been avoided in this case, the Co, Cu, and Al, in whatever chemical form they remain, must be

reprocessed into battery-ready materials. The processes required to do this are not clear, but they certainly would require energy.

Finally, one company, OnTo, has developed a process that recovers anode and cathode materials in a form that can be reused in batteries. This effort is novel and unique, and it offers a way to reuse these valuable materials without taking them back to elements. This approach offers the promise of reduced CTG production energy for these batteries. Some preliminary energy values associated with this approach are available at this time, though it is difficult to associate specific energy values with the components.

The authors are unaware of any infrastructure and approach for recycling Na/S batteries. Clearly, the steel, copper, and aluminum in the system can be recycled, but a process to recycle sodium and sulfur from these batteries is still undeveloped. However, because these batteries appear to have considerable potential for grid energy storage and load leveling, a recycling system for them should be considered.

3.4 CRADLE-TO-GATE LIFE-CYCLE ENERGY COMPARISONS OF THE BATTERIES

A review of Table 2 reveals a considerable variation in E_{mp}, E_{mnf}, and E_{ctg} for each battery technology. Some of the references in the table give values for all three energies, while others provide only one. The noted variation has been mentioned before (Rydh and Sanden 2005). There are a number of reasons for it, including location effects (Europe vs. North America), dated and missing information, data compiled from numerous sources, battery application (photovoltaic vs. automotive), and uncertainties in material requirements and manufacturing processes. The variation is about the same across all technologies. When averaging within each technology and employing only those values where both E_{mp} and E_{mnf} are given, the coefficient of variation ranges from 23% to 29%.

As seen in Figure 3, the magnitude of battery E_{ctg} trends upward in the following order: Pb/A, NiCd, Li-ion, Na/S, and NiMH. It is clear that PbA has the lowest production energy, possibly followed by NiCd batteries. However, given the magnitude of the standard deviations seen in the figure, the E_{ctg} values for the Na/S, Li-ion, and NiMH batteries are statistically indistinguishable based on this data set. With the exception of NiCd, the same trend is observed if expressed on a per watt-hour capacity basis (see Figure 4). In that case, the NiCd battery energy value is statistically equivalent to the other advanced batteries.

The material production results in Table 2 for all batteries, except PbA, are assumed to be from virgin sources. The PbA batteries have long used recycled Pb, and the values listed in Table 2 and Figure 3 already have recycled content implicitly included. However, even if PbA batteries were made using strictly virgin materials, their E_{ctg} value (≈ 40 MJ/kg) would still be considerably lower than those of the other batteries. Incidentally, using the data of Rydh and Sanden (2005) and their E_{mp} values for recycled materials, we estimate that the E_{ctg} would
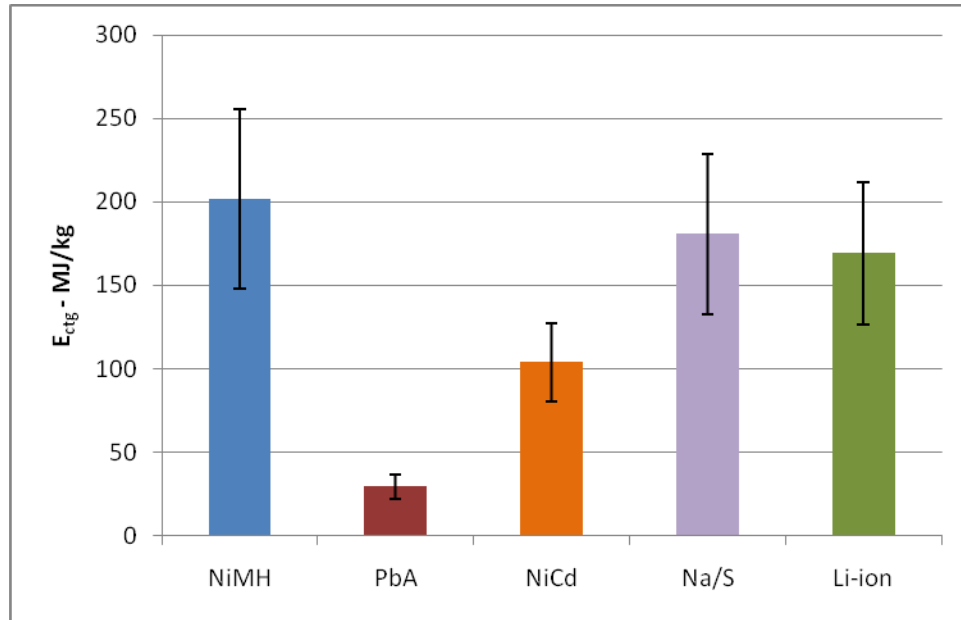
FIGURE 3 Average E$_{ctg}$ Values ± One Standard Deviation for the Various Battery Technologies (the materials production component is solely from virgin sources, except for PbA)
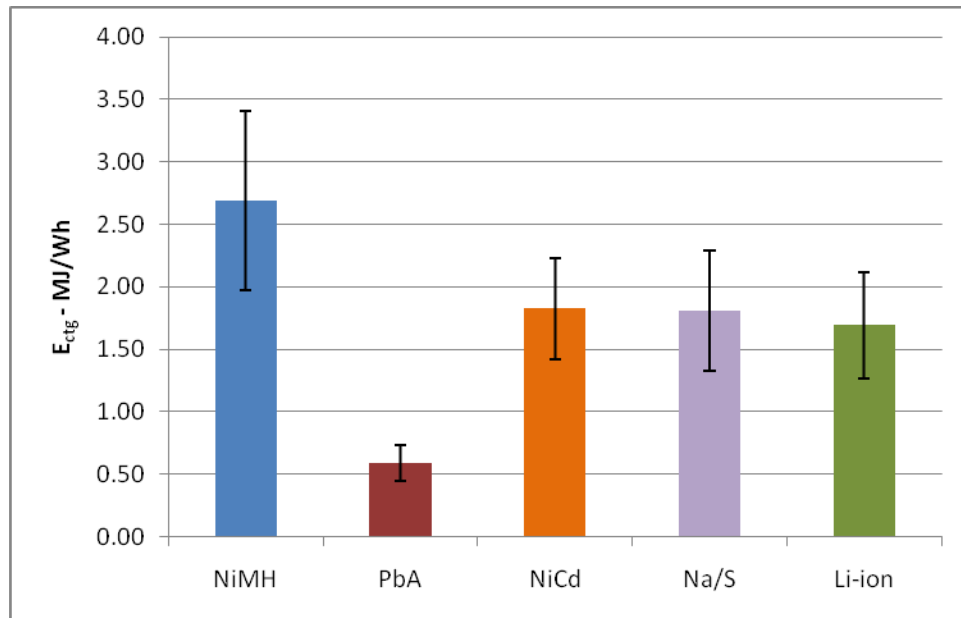

FIGURE 4 Average E$_{ctg}$ Values ± One Standard Deviation for the Various Battery Technologies, as Shown on a per Watt-Hour Basis (same information as in FIGURE 3, except on a per watt-hour basis)

decrease by about 25%, 30%, 25%, 36%, and 20% for NiMH, PbA, NiCd, Na/S, and Li-ion batteries, respectively. Though these improvements are substantial, the values must be considered provisional due to uncertainty about the PE_j values for recycled battery materials.

Figure 5 shows the E_{mp} component of the E_{ctg} estimated from constituent material PE_j values. For comparison purposes, range values from Table 2 are also included. The E_{mp} values were estimated for PbA, NiCd, NiMH, and Na/S batteries, but not for Li-ion due to a lack of materials production data. The figure shows that our estimates fall within the range found in Table 2, but with the exception that PbA batteries tend to be on the high side of the range. This suggests that our virgin material production data need updating, especially for the advanced battery systems. The PbA battery estimate is based on a 50/50 virgin/recycled Pb mix and 100% recycled polypropylene.

Another trend, which can be estimated from Table 2, is the manufacturing stage's share of E_{ctg}. It is as follows: (1) about a third for PbA and Na/S, (2) about half for NiMH and NiCd, and (3) inconclusive for Li-ion batteries due to the breadth of the distribution of values. Generally speaking, better descriptions of current battery manufacturing processes are needed. Knowing at least something about the processes provides the life-cycle analyst with an opportunity to estimate associated energy consumption by using informed judgment based on experience with the same types of processes used for other systems.

In summary, the status of life-cycle energy data for battery production is as follows: updated material production data are needed, and data gaps should be filled. In addition, process descriptions and material and energy flow data are needed for battery manufacturing. More specifically, material production data for Ni, Al, steel, polypropylene, and nylon are complete, current, and of high quality. Although dated, the existing material production data for many other
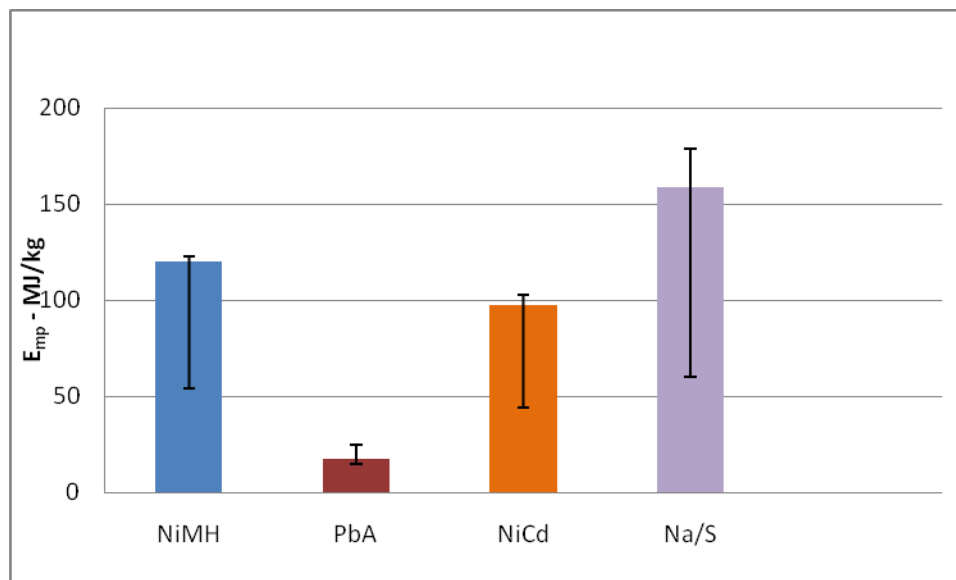

FIGURE 5 Estimated E_{mp} (MJ/kg) for Various Batteries from Virgin Materials (including range information)

battery materials, such as Pb, PbO, Na, and S are adequate for battery production life-cycle estimations. Unfortunately, the PE_j (and ideally $\{B\}_j$) values for materials used in advanced battery technologies, such as $LiCoO_2$, Cd, β-alumina, mischmetal hydrides, and others, are either missing, dated, or of unknown quality. With the exception of PbA batteries, published life-cycle data on battery manufacturing and assembly processes are generally unavailable, though some non-quantitative descriptions of process chains and flows have been published, as discussed in Section 3.2. This renders the manufacturing energy and emissions values reported herein as place holders and approximate. It is also evident in Table 2 that comparatively little life-cycle data are available on making batteries from recycled materials, and the data that do exist is poorly documented. Given the significant benefits estimated above for E_{mp} using recycled materials, more complete and better documented data are needed for material production from recycled materials.

Clearly, there is a need for systematic life-cycle studies of battery technologies. Indeed, the U.S. EPA is currently sponsoring a multi-company life-cycle study for Li-ion batteries.

3.5 EMISSIONS ANALYSIS

Thus far, the focus has been on the CTG energy analysis and its components for five rechargeable battery types. The literature has fewer life-cycle publications where emissions are tracked. Nonetheless, a range of emissions data have been reported, including CO_2 emissions; criteria pollutants (due to combustion); and process-specific emissions (e.g., heavy metals), both to air and water; and solid waste. With the exception of one reference (Rantik 1999), combustion-related emissions (CO_2 and criteria pollutants) are recorded for all other references cited in this section, either by directly reporting the values given by the authors (Gaines et al. 2002; Ishihara et al. 1999; Kertes 1996) or by computing them using GREET and the fuels data cited in the references (Hittman Associates 1980; Rydh and Sanden 2005; GREET 2010). Although a few sources of process-specific emissions and solid-waste flows have been included here (Gaines 2002; Rantik 1999; Kertes 1996), such data are typically less frequently reported in the literature.

The emissions data found in the literature are recorded in Tables 12 and 13, the latter of which records a very limited set of recycling emissions data. With the exception of Rantik (1999), only those values that include both the material production and battery manufacturing stages are recorded. Though some emission values can be found in EVTECA (1998), they also are not recorded in the tables, because the battery manufacturing stage is not adequately covered.

3.5.1 Carbon Dioxide Emissions

Tables 12 and 13 list all relevant combustion gases individually. We do not report aggregate GHG emissions. The interested reader can convert the CO_2, N_2O, and CH_4 listed in the tables to GHG $(CO_2)_{eq}$ by using well-established equivalency factors. In general, GHG emissions per kilogram of battery are at most a few percent greater than direct CO_2 emissions.

TABLE 12 Air, Water, and Solid Wastes for Cradle-to-Gate Battery Production (g/kg of battery, unless otherwise stated)

Technology	VOC	CO	NOx	PM	SOx	CH$_4$	N$_2$O	CO$_2$	Water	Air	Reference
				g/kg				kg/kg	mg/kg		
NiMH	0.11	0.34	1.31	0.79	1.06	1.33	0.04	1.02	60 g Al, Ni, Co, etc., to air/water/solid		Rantik 1999[a]
	1.3	4.5	27	2.8	263	22.7	0.19	14.8	18[b] – heavy metals	100[b] – heavy metals	Gaines et al. 2002
			19		14			15			Ishihara et al. 1999
	0.7	2.1	8.7	14.0	19.2	11.1	0.11	8.3			GREET 2.7
	0.9	3.9	11.4	18.9	20.5	15.3	0.1	10.3			Rydh and Sanden 2005[c]
	1.8	7.5	21.8	36.1	38.9	29.3	0.3	19.5			Rydh and Sanden 2005[c]
Average	1.2	4.5	17.6	18.0	71.1	19.6	0.2	13.6			
PbA	0.11	0.31	1.13	1.67	2.29	1.64	0.02	1.1	4.8 – Pb	1.2 – Pb	Rantik 1999[a]
	2.2	1.3	7.9	.8	10.3	.002	0.006	1.1	97 – heavy metals	118 – heavy metals	Kertes 1996
			5.8		5.3			5.1			Ishihara et al. 1999
	0.57	1.65	6.8	11.0	14.9	8.7	.09	6.4			GREET 2.7
	0.2	0.6	1.5	1.3	2.0	3.0	0.02	1.4			Hittman Associates 1980
	0.2	0.7	2.1	3.5	3.7	2.9	0.0	1.9			Rydh and Sanden 2005[c]
	0.3	1.2	3.5	5.7	6.0	4.6	0.0	3.1			Rydh and Sanden 2005[c]
Average	0.7	1.1	4.6	4.5	7.0	3.8	0.0	3.2			
NiCd									60 – Cd, Co, Ni	40 – Cd, Co, Ni	Rantik 1999[a]
	5.9	5.4	40	5.2	265	0.001	0.015	6.2	30 – heavy metals	740 – heavy metals	Kertes 1996
	0.6	1.9	8.6	11.3	16.9	9.5	0.1	7.3			Ishihara et al. 1999
	0.7	2.8	8.1	13.4	14.5	10.9	0.1	7.3			Rydh and Sanden 2005[c]
	0.9	3.8	11.1	18.3	19.8	14.9	0.1	9.9			Rydh and Sanden 2005[c]
Average	2.0	3.5	17.0	12.1	79.0	8.8	0.1	7.7			
Na/S	1.67	5.4	20.5	25.6	38.0	27.3	0.2	18.2			Hittman et al. 1980
	1.1	4.4	13.0	21.4	23.4	17.3	0.2	11.6			Rydh and Sanden 2005[c]
	1.2	4.9	14.6	24.2	26.5	19.6	0.2	13.2			Rydh and Sanden 2005[c]
Average	1.3	4.9	16.0	23.7	29.3	21.4	0.2	14.3			

TABLE 12 (Cont.)

Technology	VOC	CO	NOx	PM	SOx	CH$_4$	N$_2$O	CO$_2$	Water	Air	Reference
				g/kg				kg/kg		mg/kg	
Li-ion			22.5		17.5			18.2			Ishihara et al. 1999
	0.6	1.8	7.6	17.3	16.7	9.7	0.1	7.2			GREET 2.7
	1.1	4.3	13.3	21.9	24.9	17.6	0.2	12.1			Rydh and Sanden 2005[c]
	1.7	6.4	20.0	32.9	37.4	26.5	0.2	18.1			Rydh and Sanden 2005[c]
Average	0.9	3.0	14.5	19.6	19.7	13.7	0.1	12.5			

[a] Does not include battery material production.
[b] Solely from Ni production; assumed battery is 25% Ni.
[c] Used the average of their total energy values cited in Table 2.

TABLE 13 Emissions to Air, Water, and Solids for Battery Recycling (g/kg battery, unless otherwise stated)

Technology	VOC	CO	NOx	PM	SOx	CH$_4$	N$_2$O	CO$_2$	Water	Air	Reference
				g/kg				kg/kg		mg/kg	
NiMH	0.107	0.386	1.390	2.047	2.786	1.619	0.016	1.234	0.24 kg slag and 30 g toxics – solid		Rantik 1999
PbA	0.425	1.762	1.966	0.520	0.522	0.768	0.025	0.604	< 0.1 Sb, Hg, Ni, Pb, etc	5.0 – Pb, Cd, Cu, Zn, As	Rantik 1999
NiCd	0.111	0.429	3.1	0.386	2.71	0.492	0.014	0.378	< 0.1– Cd, Ni	1.0 – Cd, Ni	Rantik 1999

To facilitate a comparison of the data, battery production CO_2 emissions are presented in Figure 6. The values shown are all CTG values. As expected, the relative trends between the technologies seen in the figure are virtually the same as those seen in Figure 3. In summary, the ranked list of CO_2 emissions per kilogram of battery in increasing order is: lowest for PbA, higher for NiCd, and highest for the remaining advanced technology batteries. Due to the magnitude of the variation seen in the figure, the average CO_2 values for Li-ion, Na/S, and NiMH are concluded to be statistically equivalent based on this data set. Given the equivalent trends seen in Figures 3 and 6, we expect that a chart of CO_2 emission per watt-hour battery capacity would show the same trend as seen in Figure 4.

The CTG CO_2 values shown in Figure 6 for Hittman (1980) and Rydh and Sanden (2005) were calculated from their fuel data using GREET. Because the Hittman report lists primary energy values by fuel type, those data were easily processed in GREET to yield emissions results. Also, from the electricity fraction of total primary energy values provided by Rydh and Sanden (2005), and assuming that the rest of the energy (not specified by them) is a 50/50 mix of coal and natural gas (typical process fuels), emissions values were again readily computed in GREET from the E_{ctg} values. The values shown in the figure assume virgin materials in the material production stage, except for PbA batteries, which as a matter of practice already have a substantial recycled Pb content. The effects of material recycling on battery production CO_2 emissions for all battery technologies is anticipated to mirror the reductions discussed above for energy.
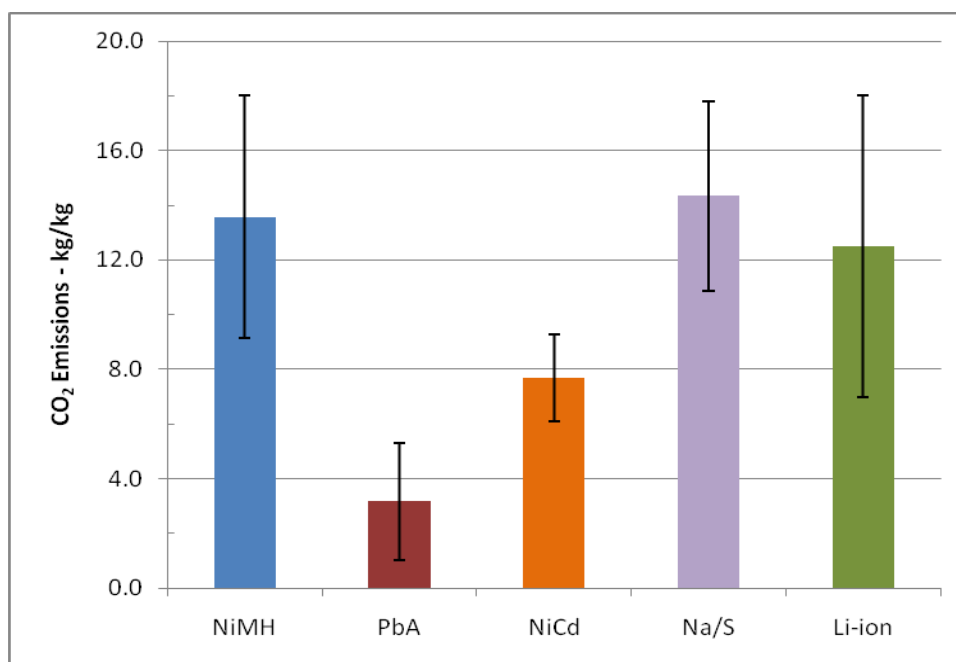

FIGURE 6 Average CTG CO_2 Emissions ± One Standard Deviation for the Production of a kg of Various Battery Technologies

From energy consumption data given by Rantik (1999), we also calculated a set of CO_2 emission values for battery recycling. Those values are shown in Table 13 for three battery technologies. While his values represent the recycling of a kilogram of battery, simple mass allocation permits attribution of energy and emissions to recycling system output. These are: for PbA battery recycling, 100% of the CO_2 values can be attributed to Pb (recycling in Sweden; Kertes 1996); for NiCd battery recycling, about 25% and 75% of the CO_2 are assigned to Cd and ferronickel, respectively; and for NiMH recycling, around 53% and 32% of the CO_2 belong to ferronickel and iron/steel, respectively. Kertes reports on emissions for battery recycling. However, because an unspecified credit has been applied to them, some of the emission values compute to negative values and therefore are not cited here.

3.5.2 Criteria Pollutants

Tables 12 and 13 also list the CTG combustion-related criteria pollutants for the five batteries. The variation in these results is generally larger than those for energy and CO_2 emissions. With the exception of SO_x emissions for NiMH and NiCd batteries, the emission averages for each technology are less than 20 g/kg of battery for all emission types, and the relative variation of the averages across battery technologies for each emission is about the same. In fact, the coefficient of variation for all but SO_x emissions ranges between 0.38 and 0.48. To facilitate comparison, these averages are plotted in Figure 7. Clearly, the SO_x emission averages for the NiCd and NiMH are outliers, which is due to the very high SO_x emissions reported by Gaines et al. (2002) and Kertes (1996) (see Table 12). A substantial part of those emissions is not the result of combustion, but is incurred during roasting of Ni sulfide ores and Cd production.
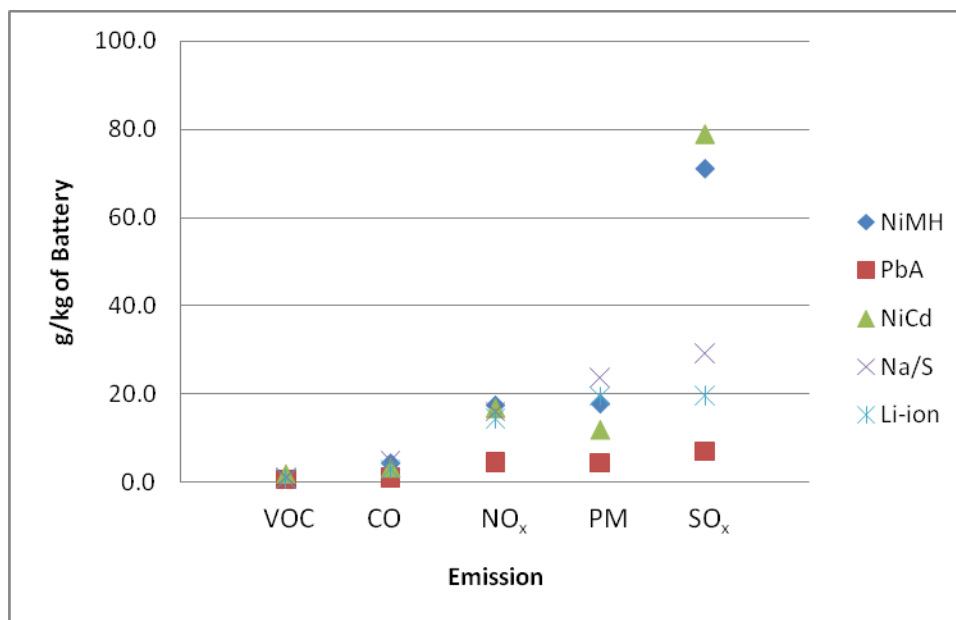

FIGURE 7 Average Criteria Pollutant Emissions (grams) per Kilogram of Battery for Five Batteries

Indeed, if Cd production SO_x emissions are eliminated, then Kertes's NiCd sulfur emissions change from 265 to about 20 g/kg of battery.

When plotted on a watt-hour capacity basis (see Figure 8), the results trend (not shown) the same way as in Figure 7, though the gap between the advanced battery and PbA results narrows.
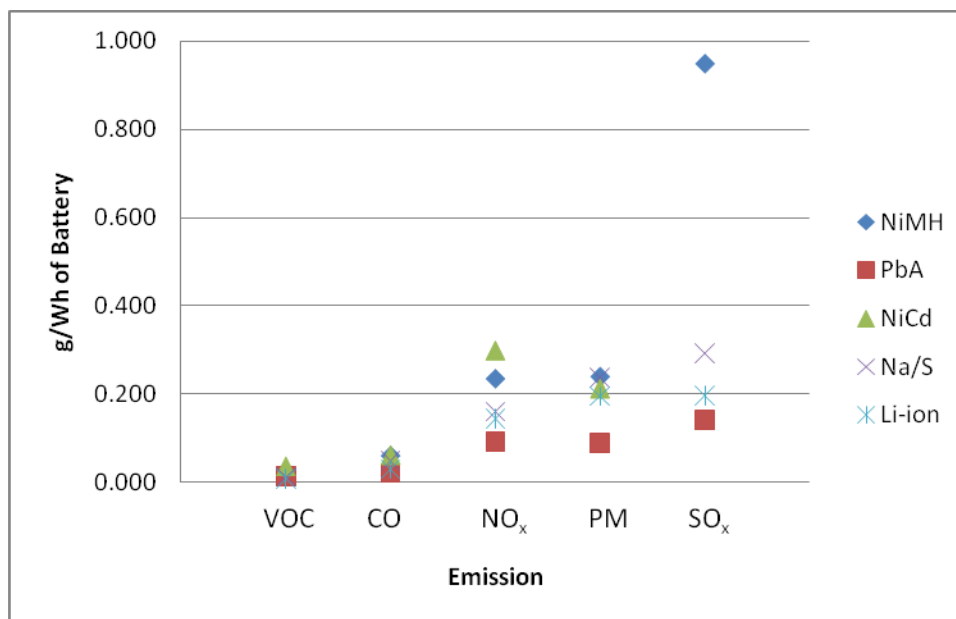

FIGURE 8 Average Criteria Pollutant Emissions (grams) per Wh of Battery Capacity for Five Batteries

The Rantik (1999) results are not included in these averages, since they represent only the battery manufacturing stage. Of the data listed in the table, the data of Gaines et al. (2002), Ishihara et al. (1999), and Kertes (1996) are taken directly from their publications; all others are computed from cited fuel consumption data using GREET. It is clear from the figure that criteria pollutant emissions per kilogram of PbA battery are less than any of the other battery technologies. Otherwise, there appears to be no trend of emissions with battery technology.

3.5.3 Other Emissions

Process-specific air, water, and some solid waste emissions are also recorded in Tables 12 and 13. Not surprisingly, given the industry and the materials being considered, these emissions values are dominated by heavy metals, both to air and water. Unfortunately, only a couple of sources for such data have been found, thus making it difficult to make comparisons between the battery technologies. Further, the data listed for Rantik (1999) represent only the battery manufacturing stage, whereas those emissions by Gaines represent Ni production.

Because the variation ranges from one to three orders of magnitude, it is clear that better and more current data for these emissions are needed.

3.6 USE OF RESULTS IN PRODUCT LIFE CYCLES

The objective of this report has been to review published CTG energy and emissions for five battery technologies, regardless of their application. To use these results in product life cycles, the application (grid energy storage, vehicles, and consumer products) must be considered. In the case of batteries, properties such as specific energy (SE), cycle life (CL), depth of discharge (DOD), charging/discharging efficiency (η_{bat}), and mass (m_{bat}) need to be included in the analysis. However, an inspection of Table 1 shows a considerable range in these properties for each of the technologies. Further, properties (such as CL) are a function of DOD. A true measure of a battery's life-cycle performance is the amount of service rendered — in this case, lifetime kilowatt-hours delivered.

For example, the total life-cycle energy of a battery (LCE_{bat}) in a particular application is dependent on the expected lifetime service demand (kilowatt-hours) and battery properties. More specifically:

$$LCE_{bat} \ = \ Demand * E_{ctg} / (m_{bat} * SE * CL * DOD). \tag{4}$$

In short, based on the demand, the LCE_{bat} for the application is the number of batteries needed times the E_{ctg}. However, the LCE_{bat} is just one component of a product system's life-cycle energy. Suppose that a battery electric vehicle is being considered. The total life cycle energy for the vehicle is:

$$LCE_{vh} \ = \ LCE_{mp} \ + \ LCE_{assm} \ + \ LCE_{op} \ + \ other, \tag{5}$$

where vh denotes vehicle, mp means total vehicle material production, op stands for vehicle operation, and "other" denotes terms like maintenance repair and end-of-life, which are usually quite small. As pointed out above, LCE_{bat} is a component of $LCE_{mp} + LCE_{assm}$. For LCE_{op}, in magnitude the largest term in equation (5), we write:

$$LCE_{op} \ = \ LTDST / (EF_{pt} * \eta_{bat} * \eta_{chrg} * \eta_{el}), \tag{6}$$

where LTDST is the lifetime drive distance; EF_{pt} is the average energy efficiency of the powertrain (e.g., mi/kWh); and the ηs are the efficiencies of the battery (bat), charger (chrg), and grid (el), respectively. Note that EF_{pt} is dependent on vehicle mass, to which m_{bat} contributes.

The above illustrates that those intending to use battery life cycle results must keep in mind both physical and performance characteristics of the battery and their impact on the product system being evaluated.

4 CONCLUSION

A review has been conducted on CTG LCI results for the production of batteries. Material production data are available for some battery constituent materials and the commodity materials from which they are made. A more limited set of data was found for the manufacturing stage of the battery life cycle. Unfortunately, the quality of the data is variable. Some of the references provide speciated fuels data and process descriptions, while others provide considerably less.

Based on existing material production data for battery materials, estimates of battery material production were made and found to be within the range of existing data. However, there is considerable variance in the existing data. Due to a lack of material production data, the same estimates could not be done for Li-ion batteries. Better estimates of battery material production are also needed for some materials in NiMH and NiCd batteries.

Whether on a per kilogram or per watt-hour capacity basis, the CTG production energy of PbA batteries is the lowest of the five batteries reviewed. On a per kilogram basis, NiCd is the next lowest, with the remaining batteries tied, given the variation in results. On a watt-hour basis, all batteries except PbA are tied. When ranked on a CO_2 emissions basis, the trend among the batteries is the same as that observed in the case of production energy. The PbA batteries also have the lowest CTG criteria pollutant emissions among the batteries.

From our assessment of the CTG life-cycle data, we conclude that there is need for more material production energy data on batteries. Some of the identified material production data are quite good, but there are also data gaps and questionable results. More specifically, purchased energy data are needed for the production of PbO_2, $LiCoO_2$, $LiMn_2O_4$, $LiNiO_2$, $LiFePO_4$, $LiCo_{1/3}$, $Ni_{1/3}Mn_{1/3}O_2$, graphite (LiC_6), $LiPF_6$, $LiBF_4$, $LiClO_4$, $Cd(OH)_2$, diethyl carbonate, and ethylene carbonate. Data are also needed for the production of mischmetal hydrides and β-alumina. Descriptions of material production processes should also be developed. Energy for and descriptions of the manufacturing processes required to make and assemble batteries from their base materials are also essential. The information that exists is often dated or is estimated by using rules of thumb. Older information may not be representative of current production systems because of industry efficiency initiatives or the addition of emissions-control devices. There is also a need for emissions data from material production and battery manufacturing, especially for process-specific emissions. Finally, the reduced environmental burdens of battery production that uses recycled materials could greatly decrease their environmental impact. Therefore, more material production data for recycled materials are necessary.

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Umicore, Personal Communication

APPENDIX

TABLE A-1 Cradle-to-Gate Life-Cycle Energy (MJ/Wh) Results for Five Battery Systems

Battery	Note	E_{mp} Virgin	E_{rcycl}	E_{mnf}	E_{ctg}	Specific Energy	Reference
NiMH		1.45	0.27	0.14	1.59		Ishihara et al. (website)
					3.97[b]	59	Ishihara et al. 1999
	AB$_2$				3.25	75.8	Gaines et al. 2002
					2.57[d]		Gaines et al. 2002
	AB$_5$				4.13		Gaines et al. 2002
		0.75				75.8	Gaines and Singh 1995
		1.6	0.6[c]	2.1		35–55	Rydh and Sanden 2005
				0.17[a]		75–95	Rantik 1999
							GREET 2.7
PbA		0.53	0.19	0.27	0.87		Ishihara et al. (website)
					1.81[b]		Ishihara et al. 1999
		0.49				50	Gaines and Singh 1995
		0.77	0.45[c]	0.42		20–32	Rydh and Sanden 2005
				0.37[a]		35–55	Rantik 1999
							Kertes 1996
		0.36		0.18	0.54	50	Hittman Associates 1980
NiCd		1.81					Gaines and Singh 1995
							Kertes 1996
		2.0	1.0[c]	2.1		22–30	Rydh and Sanden 2005
Na/S		0.60				100	Gaines and Singh 1995
		1.72		0.54	2.26	104	Hittman Associates 1980
		0.8	0.29	0.6		103–116	Rydh and Sanden 2005
Li-ion	NCA-G	1.16	0.05	0.32	1.50		Ishihara et al. (website)
	LMO-G	1.15	0.02	0.30	1.46		Ishihara et al. (website)
	LiNiO$_2$				1.49–2.23[b]	100–150	Ishihara et al. 1999
	NCA-G	0.67	0.31[c]	1.2		80–120	Rydh and Sanden 2005
		1.13		0.92	2.05	100[e]	GREET 2.7
					2.22	100[e]	Umicore Slide/Virgin Materials
	NCA-G						
					0.63	100[e]	Umicore Slide/Recycled Materials
	NCA-G						

* See Section 3.1.4 for Li-ion nomenclature; E_{rcycl} denotes energy to recycle batteries.
[a] Computed from cited values of production energy per kilogram and median specific energy.
[b] Appears to be a combination of material production and battery production using "hybrid analysis."
[c] Reported as material production energy using recycled materials.
[d] Same as above, except that recycled Ni is used.
[e] These values are assumed.