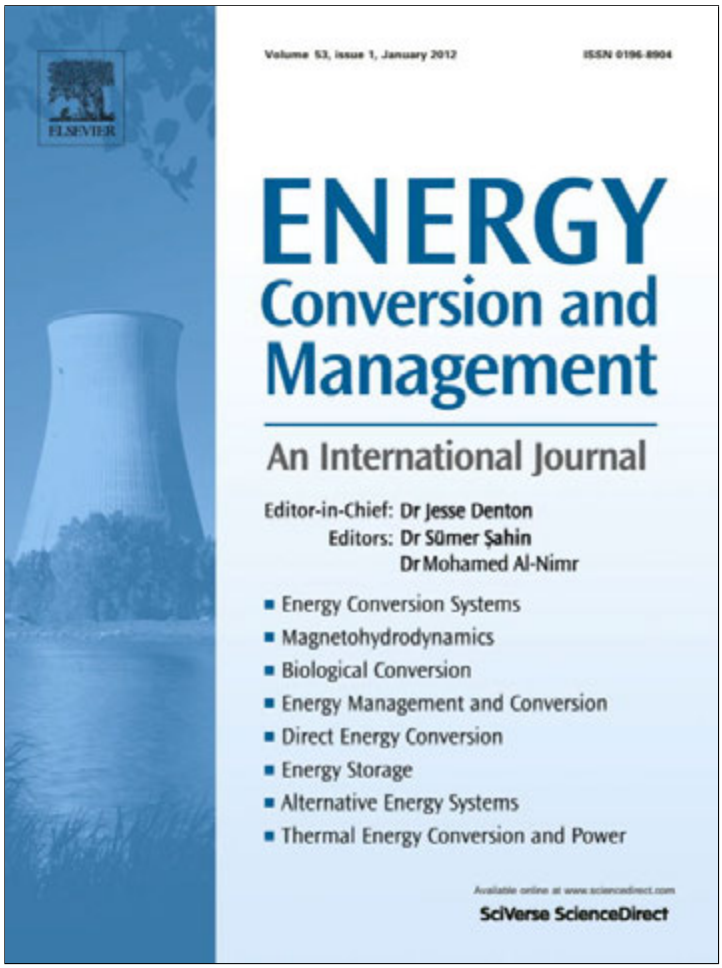
Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.




(This is a sample cover image for this issue. The actual cover is not yet available at this time.)

This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright

Author's personal copy

Energy Conversion and Management 58 (2012) 134–148

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

# Status of life cycle inventories for batteries

J.L. Sullivan *, L. Gaines

*Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, 9700 South Cass Avenue, Bldg. 362, Argonne, Illinois, IL 60439-4815, USA*

ARTICLE INFO

*Article history:*
Received 12 May 2011
Accepted 2 January 2012

*Keywords:*
Batteries
LCA
Production energy
Emissions

ABSTRACT

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.

© 2012 Elsevier Ltd. All rights reserved.

## 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

* Corresponding author. Address: Systems Assessment Section, Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, 9700 South Cass Avenue, Bldg 362, Argonne, IL 60439-4815, USA. Tel.: +1 734 945 1261; fax: +1 630 252 3443.

*E-mail address:* jsullivan@anl.gov (J.L. Sullivan).

0196-8904/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enconman.2012.01.001

Author's personal copy



**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.

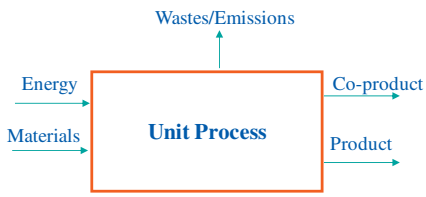



**Fig. 1.** Generalized unit process.

Author's personal copy



We divide this chain of unit processes into two separate life-cycle stages. The first is *Battery material production*. This stage 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. Ideally, burdens incurred during transport of materials between production and use should also be accounted for, though often not. Our list of battery materials include nickel (Ni), cobalt (Co), and lead (Pb) metal and salts; sheets of aluminum (Al), steel, and copper (Cu); and amounts of graphite, lithium carbonate ($Li_2CO_3$), glass fiber matte, plastic pellets, and so forth. The second stage is *Battery manufacturing*, which 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.*Cradle-to-gate battery production* denotes the sum of these two life-cycle stages. As such, it represents the environmental burdens incurred to produce a purchase-ready battery. 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 cradle to gate focus here. Because new batteries can in principle be made from recycled materials, battery recycling is also covered.

### 2.3. Metrics

The LCI burden vector $\{B\}$ for the production of batteries can be written as:

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

where *mp* denotes the material production stage of the life-cycle, and *mnf* stands for manufacturing stage, and *ctg* denotes the cradle-to-gate or cumulative burden vector up to the purchase ready product. The manufacturing (*mnf*) stage is where battery constituent materials are transformed into the components (structures) of the battery and assembly into a final product. $\{B\}$ is a generalized vector quantity representing a list, $B_i$, of environmental burdens. Examples of such burdens include generated emissions ($CO_2$, CO, $SO_x$, and others), consumed resources (ores and energy stocks), water and others. Because products are usually composed of a number of materials "*j*" in amounts of "$m_j$", $\{B\}_{mp}$ for a product is:

$$\{B\}_{mp} = \sum \{b_j\} * m_j/C_j. \tag{2}$$

where $\{b_j\}$ is the environmental burden vector for the production of each of its constituent materials, and $C_j$ is the production efficiency of putting material "*j*" into the battery. Though these production efficiencies are usually unavailable, they tend to be 0.95 or higher, and hence their omission should introduce little error. Life-cycle inventory data, $\{b_j\}$, for the production of many materials appear in databases and the literature. Useful components of $\{b_j\}$ include fuels, $CO_2$ emissions, and other emission burdens. A frequently used metric for the production of a material "*j*" is its production energy, denoted here as $PE_j$. This quantity is the sum of the energy components (fuels and electricity) of its $b_j$, expressed in a common energy unit (e.g. MJ/kg), plus the energies required to provide each of those fuels. Hence, from Eq. (2) the material production energy for the battery is:

$$E_{mp} = \sum PE_j * m_j/C_j. \tag{3}$$

An expression similar to Eq. (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* production energy for making the battery, a component of $\{B\}_{ctg}$, is:

$$E_{ctg} = E_{mp} + E_{mnf}. \tag{4}$$

Expressions like Eq. (4) can be written for various other life-cycle burdens (e.g. gasoline consumption, CO emissions) and other aggregated quantities.

## 3. The Batteries

### 3.1. Summary of battery physical properties

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. The considerable variation in properties within battery technologies listed in the table is due to a combination of factors including advances in chemistry and manufacturing and whether the battery is intended for power or energy applications. In addition to their broad ranges, there is an additional ambiguity in the specific energy values cited in the table. It is not always clear whether a cited value is based on a kg of cells or battery. Batteries are comprised of more than just cells; also included are conductors, packaging, insulators, circuit board controllers, and in the case of large cell assemblies, cooling systems.

### 3.2. Lead-acid batteries

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 (PP). Antimony (or calcium) is alloyed with the lead to suppress electrolysis of water during recharging.

The compositions of a pair of PbA batteries are given in Table 2. A typical new PbA battery contains between 60% and 80% recycled lead and plastic [18].

### 3.3. Nickel–cadmium batteries

The components of the battery are a cathode comprised of nickel hydroxy-oxide on a nickel foam, graphite or iron substrate, an anode made of metallic cadmium pressed onto a nickel wire mesh, and potassium hydroxide (KOH) electrolyte. 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 separator configuration is used for wettability purposes. The compositions for a representative pair of NiCd batteries are given in Table 3.

### 3.4. Nickel-metal hydride batteries

The components of the batteries are: a cathode comprised of nickel hydroxyl oxide on a nickel foam substrate, an anode of mischmetal (Me) hydrides on a nickel or a nickel plated steel mesh, KOH electrolyte, and a separator of a porous polypropylene membrane. 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

Author's personal copy



**Table 1**
Key properties of various battery technologies.

| Technology | Application[a] | Specific energy (Wh/kg) | Cell OCV[d] | Cycle life | % Energy efficiency |
|---|---|---|---|---|---|
| PbA | EV [1] | 35–50 | 2.1 | 500–1000 | 80+ |
| | PV [9] | 20–32 | | 700[b]–1500[c] | 70–84 |
| NiCd | EV [1] | 40–60 | 1.3 | 800 | 75 |
| | PV [9] | 22–30 | | 1200[b]–5500[c] | 65–85 |
| NiMH | EV [1] | 75–95 | 1.25–1.35 | 750–1200 | 70 |
| | PV [9] | 35–55 | | 1,000[b]–2900[c] | 65–85 |
| Li-ion | EV [16] | 114 | 1.85 | >800 | |
| | PV [9] | 80–120 | | 6000[b]–8500[c] | 85–95 |
| Na/S | EV [2] | 100 | | | |
| | PV [9] | 103–116 | | 4700[b]–7200[c] | 75–83 |

[a] EV = electric vehicle; PV = photovoltaic energy.
[b] Cycle life at 80% depth of discharge.
[c] Cycle life at 33% depth of discharge.
[d] Open circuit voltage.

**Table 2**
Composition (percent by weight) of two representative lead-acid battery.

| Item | Industrial [17] | EV battery [2] |
|---|---|---|
| Lead | 25 | 69[a] |
| Lead oxides | 35 | |
| PP | 10 | 4 |
| Sulfuric acid | 10 | 11 |
| Water | 16 | 18 |
| Glass | 2 | 4 |
| Antimony | 1 | |

[a] Comprised of a 1:3 ratio of lead to lead oxides.

**Table 3**
Percent materials composition of a pair of nickel–cadmium battery.

| Item | Automotive [2] | Portable electronic [11] |
|---|---|---|
| Cd | 25 | 16.4 |
| Ni powder | 20 | 20.5 |
| $Ni(OH)_2$ | 17 | 8.1 |
| KOH | 5 | 3.5 |
| Plastics | 3 | 3.7 |
| Steel and copper | 16 | 39 |
| Water | 12 | 8 |
| Other | 2 | |

**Table 4**
Percent by weight composition of two NiMH batteries: [1].

| 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 | | 8 |
| KOH | 3 | 3 |
| PP | 5 | 5 |
| Steel | 44 | 44 |
| Other | 11 | 10 |

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).

Representative compositions of a NiMH batteries are given in Table 4 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 such as those in hybrid electric vehicles tend to have less electrically active material than high-energy batteries, the latter of which would be used for traction in either all or plug-in electric vehicles. At this time, power tools are the only energy applications for NiMH batteries.

### 3.5. Lithium-ion batteries

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 5 lists Li-ion battery components and constituent materials, as well as a number of cathode and anode materials.

For convenience, we use the following nomenclature 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), (3) manganese oxide (LMO), or a mixture of Ni, Co, and Mn (NCM). Anodes are either graphite (G) or lithium salt of titanium oxide (TiO).

Table 5 lists the weight percent of components for three Li-ion battery applications. Consistent with their chemical diversity, a number of component constituent materials are also listed there. Note that the weight percent of electrode materials varies considerably. This is related to battery application, capacity, and packaging.

### 3.6. Sodium–sulfur batteries

These batteries require energy to keep them at operating temperature (ca 300 °C). Nonetheless, NaS batteries have good specific energy and cycle life and are currently being used in Japan and the US for grid energy storage. Example cell and battery compositions are shown in Table 6. These batteries are distinct from the other batteries discussed thus far. For them, the electrodes are liquids and the electrolyte is a solid, whereas for the other batteries, the electrodes are solids and the electrolyte is liquid. In the case of Na/S batteries, the cathode is molten sulfur, the anode is molten sodium, and the electrolyte is solid β-alumina.

## 4. Cradle-to-gate energy

### 4.1. Published energy data summary

For each battery technology, $E_{ctg}$, $E_{mp}$, and $E_{mnf}$ on the basis of per kilogram of battery, have been extracted from the literature and are listed in Table 7. For the interested reader, using provided specific energy values, table values can be converted to a per Wh basis. The averages given in Table 7 are based only on those values where both $E_{mp}$ and $E_{mnf}$ were reported. Because these energy values are mostly 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 and criteria pollutant emissions were

Author's personal copy



**Table 5**
Percent by weight composition of Li-ion batteries; material composition where available are listed as (%) of component weight.

| Component | Example materials | PHEV 20[c] | PHEV 40[c] | EV [3][d] | Laptop |
|---|---|---|---|---|---|
| Cathodes | $LiCoO_2$, $LiMn_2O_4$ $LiNiO_2$, $LiFePO_4$, Al $LiCo_{1/3}$ $Ni_{1/3}Mn_{1/3}O_2$ $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ | 36 | 40 | 33 | 25 |
| Anodes | Graphite ($LiC_6$) $Li_4Ti_5O_{12}$, Cu | 31 | 29 | 21 | 20 |
| Electrolyte[b] | ECM[e] Propylene carbonate $LiPF_6$, $LiBF_4$, $LiClO_4$ | 11 | 12 | 7 | 12 |
| Separator | PP | 2 | 1 | 4 | 3 |
| Case | Steel, PE/PP, Al, Cu, Fe | 20 | 17 | 19 | 40 |
| Other[a] | Cu, PE/PP, Steel, Fe | | | 16 | |

[a] Other denotes materials like binders, recipe ingredients, and control circuitry, insulation.
[b] Includes solvents.
[c] Argonne model; $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ cathode and graphite anode batteries.
[d] Materials for this battery are underlined in column 2.
[e] EthylMethylCarbonate.

**Table 6**
Percent material composition for EV sodium–sulfur batteries.

| Material | [4] | [19] [a] | [19] [a] |
|---|---|---|---|
| | Cell | Cell | Battery |
| Sulfur | 29.4 | 21.6 | 12.5 |
| Sodium | 17.8 | 13.8 | 8 |
| β-Alumina | 2.7 | 17.7 | 10.2 |
| α-Alumina | 1 | 3.9 | 2.3 |
| Steel | 13 | 0.3 | 12.8 |
| Aluminum | 15.3 | 36.4 | 22.7 |
| Graphite | 2.5 | | |
| Copper | 4.2 | | 3.4 |
| PP | 7.7 | | |
| Glass | 1.4 | | 4.3 |
| Sand | | | 15.2 |
| Miscellaneous | | | 8.7 |

[a] Battery used for EV analysis in this reference.

calculated. Both process and combustion emissions are discussed in a separate section.

### 4.2. Material production energy

As per Eq. (3), $E_{mp}$ for any battery is a calculated quantity. The exercise that follows compares previously published values with our estimates. An overview of the production of many of the materials in the batteries has been presented before [2,4,6,20]. This report encompasses those and more recent results. It also addresses the adequacy of the cited and published LCI data for estimating battery $E_{mp}$ values.

As indicated by Eq. (3), $PE_j$ values are required for calculation of $E_{mp}$ for the various batteries. The $PE_j$ values employed herein, along with grades for process and energy detail provided in the reference, are compiled in Table A1. Where multiple entries are given, they are listed from the most recent to the most dated. From the table, it appears that $PE_j$ have decreased over time for Pb from ore or scrap, and increased for Ni. The age of LCI data can be important. In general, one expects $PE_j$ values to decrease over time. For example, the German Plastics industry [21] claims to have reduced its energy consumption by 17% to produce the same amount of plastics. These trends of decreasing $PE_j$ over time are the result of manufacturing process efficiency improvements, which were likely driven by emission regulations and energy costs. On the other hand, in some cases, older LCI energy data might be lower than current values. An example of that is seen in Table A1 for nickel. Two potential reasons are: (1) the recent study was more comprehensively conducted, and (2) previous values based on single companies vs. the recent Nickel Institute study, which was based on nine companies representing 55% of world Ni production. Recognizing these uncertainties and given our objective of estimating battery life-cycle energy and emissions, we chose LCI data that in our judgment represents both the most recent and detailed results. Our choices of $PE_j$ are indicated in bold print in the table.

In the review of battery $E_{mp}$ data that follows, substantial ranges are observed within each technology. Because estimating $E_{mp}$ has required gathering data from multiple sources, such ranges are not surprising. The observed variations in $E_{mp}$ values within battery technologies can be attributed to combination factors, including study to study variations in: (1) battery composition, (2) battery mass accounted for, (3) $PE_j$ values, (4) location of the *mp* and *mnf* boundary (boundary blur), and finally (5) virgin to recycled (V/R) material content. Incidentally, V/R is a nominal value that was applied to all materials in a battery where $PE_j$ data for recycled constituents where available. Hence, due to the absence of $PE_j$ for some battery materials, the actual overall battery recycle content is lower. In discussion that follows, the actual recycled content appears as a percentage in parentheses following the V/R ratio.

Fig. 2 displays the results of our analysis. The three sets of columns show our $E_{mp}$ calculations for the five batteries made from purely virgin, purely recycled, and a 30/70 V/R blend of materials. The bars immediately adjacent to the columns in the figure indicate the range of study to study variation of $E_{mp}$ estimates found in the literature (see Table 7) for batteries made from virgin and recycled materials, respectively. Our calculations were based on battery compositions given in Tables 2–6, and $PE_j$ values (in bold print) for the constituent materials shown in Table A1. The obvious trends seen in the figure are: (1) our $E_{mp}$ values based on virgin materials fall within their associated range, and (2) with the exception of PbA batteries, calculated $E_{mp}$ values based on recycled materials fall well above the ranges shown. Reasons for the lower recycled $E_{mp}$ values taken from the literature might be overly optimistic values for recycle content and $PE_j$ values.

#### 4.2.1. Lead acid batteries

For the industrial PbA battery given in Table 2, our estimated "virgin" $E_{mp}$ is 26 MJ/kg. As seen in Fig. 2, this value is at the top of the "virgin" range. However, in practice PbA batteries are made from a V/R mix of materials (Pb, $PbO_2$, polypropylene). To the industry's credit, lead acid batteries are one of the most highly recycled products. Given the battery industry's record and assuming V/R = 30/70 (50%), we estimated $E_{mp}$ to be 12.7 MJ/kg, which is 51% less than the virgin value just cited. We chose this mix because it falls midrange of lead acid battery industry claims [18]. Because our two estimates (26 and 12.7 MJ/kg) closely agree with the observed range in the figure, we conclude that the observed range is due primarily to variation in the V/R ratio. However, variation in

Author's personal copy



**Table 7**
Cradle-to-gate life-cycle energy (MJ/kg) results for five battery systems[a]: listed averages are based on data where both $E_{mp}$ and $E_{mnf}$ are reported. Year refers to date published.

| Battery | Note | Production energies | | | | Specific energy | | |
|---|---|---|---|---|---|---|---|---|
| | | $E_{mp}$ | $E_{rcycl}$ | $E_{mnf}$ | $E_{ctg}$ | Wh/kg | Year | Reference |
| NiMH | | 139 | | 101 | 240 | 55 | 2011 | 8 |
| | | 86.5 | | 105 | 191.5 | | 2006 | 25 |
| | | 54–102 | 21–40[b] | 74–139 | 128–241 | 33–55 | 2005 | 9 |
| | | | | | 234 | 59 | 2002 | 3 |
| | $AB_2$ | | | | 195–246[f] | | 2002 | 6 |
| | $AB_5$ | | | | 207–263[f] | | 2002 | 6 |
| | | | | 14.6 | | 75–95 | 1999 | 1 |
| | | 108 | 19.6[d] | 8.1 | 119 | | ? | 24 |
| | | 78 | | | | 75.8 | 1995 | 2 |
| | Ave | 96.1 | | 93.3 | 189.4 | | | |
| PbA | | 11.4 | | 81.9 | 93.3 | | 2006 | 25 |
| | | 15–25 | 9.0–14[b] | 8.4–13 | 23.4–38 | 20–32 | 2005 | 9 |
| | | | | 16.6 | | 35–55 | 1999 | 1 |
| | | | | | 77 | | 1999 | 3 |
| | | 16.8 | | 6.7 | 23.5 | | 1996 | 5 |
| | | 15[f] | | | | 50 | 1995 | 2 |
| | | 25.1 | 8.4[d] | 11.3 | 36.4 | | ? | 24 |
| | | 17.5 | | 8.81 | 26.1 | | 1980 | 4 |
| | Ave | 19.8 | | 9.6 | 29.5 | | | |
| NiCd | | 44–60 | 22–30[b] | 46–63 | 90–123 | 22–30 | 2005 | 9 |
| | | 44.0 | | 53.9 | 97.9 | | 1996 | 5 |
| | | 102.8 | | | | 57 | 1995 | 4 |
| | Ave | 49.3 | | 54.3 | 103.6 | | | |
| Na/S | | 82–93 | 30–34[b] | 62–70 | 144–163 | 103–116 | 2005 | 9 |
| | | 59.9 | | | | **100** | 1995 | 2 |
| | | 179 | | 56 | 235 | | 1980 | 4 |
| | **Ave** | **118** | | **62.7** | **180.7** | | | |
| Li-ion[a] | NCM-G | 121 | | 88 | 209 | 112 | 2011 | 8 |
| | LFP-G | 119 | | 86 | 205 | 88 | 2011 | 8 |
| | LMO-G | | | 1.3[d] | 104 | 114 | 2010 | 7 |
| | NCM-G | 112.9 | | 91.5 | 204.4 | | 2006 | 25 |
| | NCA-G | 53–80 | 25–37[b] | 96–144 | 149–224 | 80–120 | 2005 | 9 |
| | $LiNiO_2$ | | | | 223 | **100**–150 | 1999 | 3 |
| | NCA-G | 93.3 | 4.8[d] | 32 | 125.3 | | ? | 24 |
| | LMO-G | 113 | 3.6[d] | 30 | 143 | | ? | 24 |
| | **Ave** | **99.0** | | **81.1** | **180.1** | | | |

[c] Estimated from supplemental material.
[e] Average of their virgin and recycled materials values.
[a] See Section 3.5 for Li-ion nomenclature.
[b] Reported as material production energy using recycled materials.
[d] Reported as recycling credits to the overall battery production energy.
[f] Minimum value corresponds to using recycled Ni.

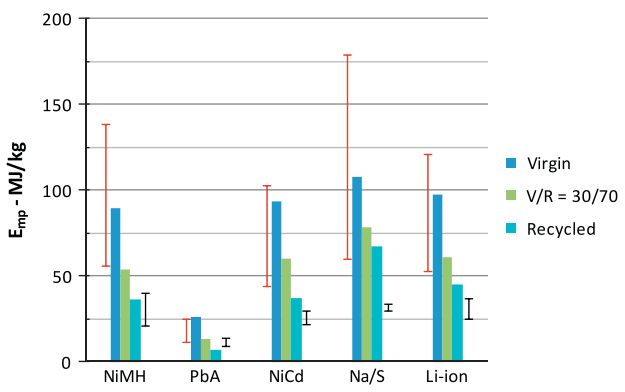



**Fig. 2.** Material production energies for the various batteries: columns denote estimates from virgin, recycled, and virgin/recycled blend materials; the range bar to the left of each cluster represents the virgin range, the bar on the right denotes the recycled range. Range values for $E_{mp}$ taken from Table 2.

the $PE_j$ values used in past studies can account for some of the range. For example, using the largest $PE_j$ values in Table A1 for virgin and recycled lead, $E_{mp}$ becomes 15.5 MJ/kg, whereas it becomes 10.7 MJ/kg using the corresponding minimum value in the table. Both of these estimates are for a 30/70 (50%) battery. Though potentially significant, it turns out that variation in battery composition has a small influence. For example, comparing the $E_{mp}$ value (30/70 mix) for the EV battery shown in Table 2 is very similar (12.1 MJ/kg) to that for the industrial battery, despite their difference in composition.

Also included in the figure is a calculated $E_{mp}$ value using 100% recycled lead, lead oxide, and polypropylene. The V/R ratio in this case is 0/100 (71%). For this hypothetical case, we compute a value of 7.0 MJ/kg, which is a 42% reduction over current practice. However, given the requirement of high purity $PbO_2$ needed for these batteries, the practical limit on the virgin/recycled materials mix is uncertain, but it is likely in the 60–80 percent range that the industry currently claims [18].

In Table 7, there appears to be no trend of $E_{mp}$ values with publication date. Even the thirty year old estimate (17.5 MJ/kg) by Hittman [4], which is based on a 47/53 mix of recycled and virgin lead in an EV battery, falls well within the ranges shown in Table 7 and Fig. 2. Our estimate for this virgin/recycled lead mix in a PbA battery is 16.9 MJ/kg, which is in reasonable accord with Hittman [4].

### 4.2.2. Nickel cadmium batteries

For the portable electronic NiCd battery given in Table 3 and $PE_j$ values in Table A1, $E_{mp}$ is calculated to be 93.2 MJ/kg, assuming 100% virgin materials. As seen in Fig. 2, this value is at the higher

Author's personal copy



end of a broad 60 MJ/kg range for the virgin estimates. Because $E_{mp}$ is 107 MJ/kg for the EV NiCd battery (see Table 3), this suggests that only some of this difference can be attributed to battery composition. The origin of the rest of the variation is likely due to significant underestimations of $PE_j$ values for virgin constituent materials. The cumulative energy for just the production on Ni and $Ni(OH)_2$ alone exceeds the low end of the range. However, incomplete material accounting and boundary "*mp1mnf*" blur might also be contributors to the observed range.

Based on $PE_j$ data for recycled nickel, cadmium, and nickel hydroxide in Table A1, we estimate $E_{mp}$ for a V/R materials content of 0/100 (94%) to be 36 MJ/kg. This represents a 60% reduction in this battery's $E_{mp}$. This value is higher than the "recycled" range, which as seen in Fig. 2 is quite narrow and low. The difference is likely due to variations in $PE_j$. A more conservative estimate of a battery with recycle content is 59.5 MJ/kg, which is a 36% reduction over a battery made from virgin material. This value corresponds to a NiCd battery with a V/R content of 30/70 (63%). For both of these $E_{mp}$ estimates, recycled steel and nylon were included. These values appear to be reasonable estimates, though more up to date $PE_j$ data for recycled Ni, Cd, and $Ni(OH)_2$ would help refine them.

The data on Cd production in Table A1 is limited. The table also lists a number of $PE_j$ values for the production of nickel. The most recent and detailed results are those provided by the Nickel Institute [22], which recently conducted a comprehensive LCI on cradle to gate production of Ni, nickel oxide (NiO), and ferronickel. The $PE_j$ values given in the Table A1 for virgin materials used in NiCd batteries are considered quite reliable. Due to its age the $PE_j$ for $Ni(OH)_2$ is probably less reliable.

#### 4.2.3. Nickel metal hydride batteries

Based on Tables 4 and A1, $E_{mp}$ values were calculated for the NiMH batteries: 89 MJ/kg for the $AB_2$ anode, and 90 MJ/kg for the $AB_5$ anode. The average of the two (89.5 MJ/kg) is plotted in Fig. 2 and falls below center of the "virgin" range. The virgin range is 85 MJ/kg, which is quite large and probably due to study to study variation in the $PE_j$. Likely contributing to this is the lack of reliable information on mischmetal production. For our calculations, an estimated $PE_j$ value of 116 MJ/kg [2] was used. The only other published value [3] is inordinately high (681 MJ/kg) and hence considered dubious. Though Kertes [5] addressed NiMH batteries in his report, he did not quantify energy or emissions for mischmetal production.

For a NiMH battery with V/R composition of 30/70 (58%) Ni, $Ni(OH)_2$, steel, and polypropylene, an $E_{mp}$ of 54 MJ/kg is obtained for both $AB_2$ and $AB_5$ batteries. This represents a 44% reduction over the virgin case. If 0/100 (82%) is assumed, the value is 37 MJ/kg. Both values, which are plotted in Fig. 2, could be lower yet if recycled mischmetal and associated $PE_j$ were available. Unfortunately, battery mischmetal is currently not recycled.

#### 4.2.4. Lithium ion batteries

Some representative compositions for Li-ion batteries are found in Table 5. Upon comparing those materials to available information on them in Table A1, one finds a considerable dearth of $PE_j$ data for Li-ion materials used in anodes, cathodes, and electrolytes. More specifically, $PE_j$ data for materials such as $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ and many of the other materials listed in Table 5, are sorely lacking. Because of this, only rough estimates can be made for the $E_{mp}$ of these batteries. Assuming the Ishihara composition given in Table 5 and assuming a cathode electro-active material of $LiCoO_2$, we estimated $E_{mp}$ for his EV battery to be 97 MJ/kg. This value falls in the upper half of the "virgin" range reported for these batteries. For the laptop battery, a value of 112 MJ/k was obtained. Unlike the PbA battery, material composition differences appear to account for about 20% of the "virgin" range (66 MJ/kg). Because LCI data for the production of $LiCoO_2$ was not available, its $PE_j$ was estimated based on $PE_j$ for $Li_2CO_3$ and Co from ores. The production step of converting $Li_2CO_3$ and $Co_3O_4$ to $LiCoO_2$, a high temperature process, could not be accounted for. Due to this omission, our estimated $E_{mp}$ certainly falls short. Hence, the observed virgin range for this battery must be due in large part to a lack of representative $PE_j$ values.

Assuming that a 30/70 (55%) V/R content for $LiCoO_2$, graphite, steel, aluminum, and plastic can be used to make this Li-ion battery, a $E_{mp}$ value of 61 MJ/kg was calculated. This amounts to an 37% reduction over the virgin value, again illustrating the energy benefit of using recycled materials in rechargeable batteries. If for these same materials only recycled stock is used, $E_{mp}$ becomes 45 MJ/kg, which amounts to a 54% reduction. However, for these values, some surrogates had to be used due to a lack of $PE_j$ values for recycled Li-ion materials. For recycled graphite, we assumed graphite extracted from the earth (see Table A1 for values). And for recycled $LiCoO_2$, we assumed that same as given above for virgin material, except the $PE_j$ for the recycled materials is assumed to be 1/3 of the virgin value. Given these considerations, most of the virgin and recycled ranges must be due to variable $PE_j$ used in past studies.

#### 4.2.5. Sodium sulfur batteries

From the composition and $PE_j$ data for Na/S battery materials given in Tables 6 and A1, $E_{mp}$ estimates range from 108 to 187 MJ/kg. The low value is plotted in Fig. 2. Overall, most of the $PE_j$ for Na/S battery constituent materials are quite good, except for the ceramic β-alumina. Indeed, it is the uncertainty of its $PE_j$ that is responsible for the large spread in the two $E_{mp}$ values just given and is likely responsible for the broad "virgin" range derived from the literature and shown in the figure. Clearly, the magnitude and hence the significance of the $PE_j$ value for β-alumina on $E_{mp}$ highlights the need for a more reliable value.

Though there is virtually no LCI information on recycling Na/S batteries, they are comprised of significant amounts of commodity materials (steel and aluminum). Hence, an $E_{mp}$ of 67 MJ/kg was made for these batteries assuming recycled steel and aluminum. This represents a 40% reduction. For a 30/70(25%) V/R content, an $E_{mp}$ = 78 MJ/kg results, which is a 28% reduction. Given the uncertainty of $PE_j$ for β-alumina, we have no explanation for why the recycled range is so narrow. Further, our $E_{mp}$ estimates for making these batteries from recycled materials are considerably higher than the literature based range, and likely due to having to use virgin $PE_j$ for β-alumina in the absence of a recycled value.

#### 4.2.6. Material production summary

For batteries made from virgin materials, our $E_{mp}$ estimates tend to be near or above the middle of the corresponding range of values found in the literature (see Fig. 2). Five factors have been identified that can lead to the breadth of the ranges. For PbA batteries, most of the $E_{mp}$ variation is likely due to study to study variation in V/R content. On the other hand, for the advanced batteries, the most significant factor appears to be study to study variation in $PE_j$ for key constituent materials, such as Ni, $Ni(OH)_2$ for NiCd and NiMH batteries, mischmetal for NiMH, Cd for NiCd, a variety of electro-active materials in Li-ion batteries, and β-alumina for NaS. Clearly, more current $PE_j$ values are needed for both virgin and recycled battery materials.

In order to estimate the benefits of recycling, estimates of $E_{mp}$ were made using available $PE_j$, even though values for some constituent materials from recycled sources were either not at hand. In short, for our V/R = 30/70 $E_{mp}$ estimates, available $PE_j$ values for recycled materials were sufficient to cover 58% of NiMH battery mass, 63% for NiCd, 50% for PbA, 55% for Li-ion, and 25% for NaS.

Author's personal copy



Commodity materials used in the batteries, such as plastics, steel, and aluminum have good well established $PE_j$, which were included in our calculations in proportion to their masses. Our "recycled" battery estimates generally exceed, sometimes by a lot, the "recycled" range derived from the literature. Again, we attribute this to a lack of reliable $PE_j$ values.

In addition to reducing $E_{mp}$, there are two other important reasons for recycling these and other batteries: (1) the conservation of valuable materials (e.g. Co and rare earth metals), and (2) in many cases, the avoidance of significant upstream air emissions associated with winning material like nickel from earth. $SO_x$ is an important example of such emissions, which are discussed later.

### 4.3. Battery manufacturing energy

This section addresses the battery manufacturing stage, which includes the processes and associated energies required to make components from constituent materials and assemble them into batteries. A summary of battery manufacturing energy data from the literature is given in Table 7. Average values of $E_{mnf}$ ($<E_{mnf}>$) have also been provided. Those are limited to data sets where both $E_{mp}$ and $E_{mnf}$ were reported.

During the manufacturing of PbA batteries, 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, assembly, and testing. 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, those products are deposited on lead grids, which also require energy for their production. $<E_{mnf}>$ for PbA batteries shown in Table 7 is 9.6 MJ/kg. (The 81.9 MJ/kg value was not used in this average, as it clearly an outlier that is almost five times as large than any of the other 6 values.) Process and energy details for the manufacture of PbA batteries can be found elsewhere [4,5]. Rantik [1] 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.

There is some LCI information on the manufacturing of NiCd batteries. Rydh and Sanden [9] cite a range of values for $E_{mnf}$, i.e. 46–63 MJ/kg of battery (see Table 7). However, they did not discuss manufacturing processes. According to Kertes [5], the manufacturing processes required to make these batteries are as follows: (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 were provided for only a few of these processes. Based on limited literature information, we report a $\langle E_{mnf} \rangle$ of 54.3 MJ/kg for NiCd batteries.

The manufacturing of NiMH batteries includes 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 [23] 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.

A summary $E_{mnf}$ values for NiMH batteries is given in Table 7, where a number of values of $E_{mnf}$ have been recorded. In an online document, Ishihara et al. [24] estimate an $E_{mnf}$ of about 8.1 MJ/kg (battery specific energy was given as 75 Wh/kg). Others have also estimated the production energy of NiMH batteries. Based on European reports [5,9], $E_{mnf}$ values for NiMH batteries range between 74 and 139 MJ/kg of battery. For the latter, no process details were given. In a proprietary report, Gaines estimates the $E_{mnf}$ to be between those values. GREET [25] lists a value of 105 MJ/kg for $E_{mnf}$ of NiMH batteries. Although speciated energy values can be found there, the energies for the unit processes that make up the entire manufacturing chain were not provided.

Overall, the range of $E_{mnf}$ values for NiMH batteries seen in Table 7 is broad and almost appears bimodal. This is probably due to two factors: (1) limited and incomplete battery manufacturing and assembly data, and (2) boundary blur (defined above).

The manufacturing of Li-ion batteries consists of a number of processes: (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 (testing); and (6) final assembly. In steps 1 and 2, heat is required to bake the paste materials spread onto the conductor strips for anodes and cathodes. For more detail, see a discussion by Gaines and Cuenca [26]. 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 lowest value in the table was extracted from process chain data given in the supplemental material given by Notter [7]. This value, 1.3 MJ/kg, seems inordinately low when compared to other $E_{mnf}$ values in Table 7. As pointed out by Majeau-Bettez et al. [8], this is four to six times lower than that required to injection or blow mold plastics [27]. The more or less intermediate value (30 MJ/kg) provided by Ishihara [3] details the manufacturing processes, including the production of solvent, $LiNiO_2$, $LiPF_6$, and indirect effects and assembly. On the other hand, the sources of the data in the high set provide no process detail. The comparatively broad range in $E_{mnf}$ values seen in Table 7 for these batteries is likely attributable to the same causes just discussed for NiMH batteries.

No detailed energy data for the manufacturing of Na/S batteries were found. Two sets of manufacturing energy data for Na/S batteries have been reported (see Table 7). The two values are in good accord. Unfortunately, neither reference provides process detail. The Hittman [4] estimate is based on a rule of thumb; that is, 25% of the total production energy is attributed to $E_{mnf}$. The other values shown in Table 7 are attributed to a European study [9]. For that battery, the energy for this stage could be considerably higher due to the production of electrolyte from β-alumina.

In summary, there are $E_{mnf}$ values available for the manufacturing 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, taken from the references, are missing adequate process description and energy detail. A broad range of $E_{mnf}$ values are found for Li-ion and NiMH systems. For greater confidence in $E_{mnf}$ values, an updated set of energy and material flow data and process descriptions are required for all of these batteries.

Author's personal copy



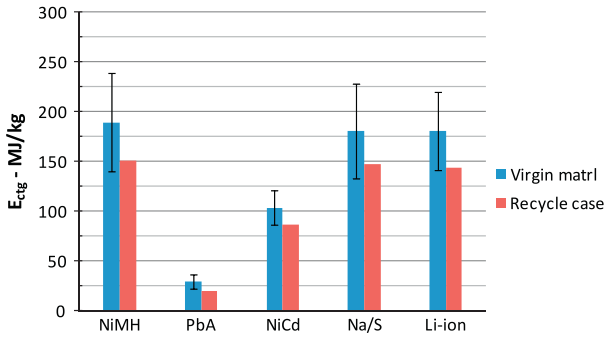



**Fig. 3.** $E_{ctg}$ values ± one standard deviation for the various battery technologies: averages are from Table 2 and values for the recycling cases were estimated for the V/R = 30/70 material mix.

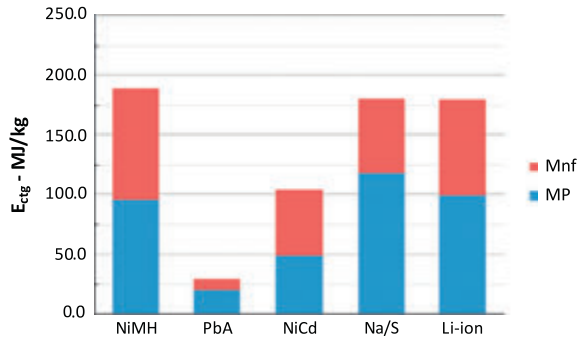



**Fig. 5.** Average $E_{ctg}$ results including its components.

### 4.4. Cradle-to-gate battery production energy

A review of Table 7 lists multiple values of $E_{ctg}$ for each battery technology. Some of the references in the table give values for $E_{ctg}$ and its comments ($E_{mp}$, $E_{mnf}$), while others provide only $E_{ctg}$. The variations in $E_{ctg}$ values listed in Table 7 are due to combinations of the factors discussed above for $E_{mp}$ and $E_{mnf}$.

As seen in Fig. 3, the magnitude of battery $E_{ctg}$ trends upward in the following order: PbA, NiCd, Li-ion, Na/S, and NiMH. It is clear that PbA has the lowest production energy, 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 basic trend is observed if expressed on a per watt-hour capacity basis (see Fig. 4). In that case, the NiCd battery energy value is now statistically equivalent to those for the Na/S and Li-ion and the NiMH battery has clearly the largest value. The PbA battery's position in the ranking is unchanged. The results in this figure were computed from those in Fig. 3 using the following specific energies: 75, 50, 57, 100, and 100 Wh/kg for the NiMH, PbA, NiCd, Na/S, and Li-ion batteries, respectively.

As seen in Fig. 3, making batteries using recycled materials can reduce $E_{ctg}$. We demonstrate this in two ways. First, using Rydh and Sanden [9] data, averaging the range values in each of the virgin, recycled, and manufacturing categories for each battery, we found decreases in $E_{ctg}$ to be 27%, 28%, 24%, 36%, and 19% for NiMH, PbA, NiCd, Na/S, and Li-ion batteries, respectively. The second way uses the recycling induced $E_{mp}$ savings discussed earlier. With those values for V/R = 30/70, decreases of 20%, 33%, 17%, 18%, and 20% were found, respectively. With the exception of NaS batteries, second set values are lower than those in Set 1 by about 5–7% points. The second set of changes in $E_{ctg}$ were computed using the average virgin $\langle E_{mp}\rangle$ and $\langle E_{mnf}\rangle$ values in Table 7, and adjusting $\langle E_{mp}\rangle$ by the recycle content percent improvements in $E_{mp}$ discussed earlier.

The reductions in $E_{ctg}$ shown in the second set are smaller than their corresponding values in the first set. This is in part due to the lower recycle content (V/R = 30/70) assumed for second set. On the other hand, set 1 results are based on literature results that appear to be estimates. Hence, it is clear that more $PE_j$ values are needed for better estimates of $E_{mp}$ of batteries made from recycled materials.

Notice that the percent decreases given above for $E_{ctg}$ are smaller than the percent changes in $E_{mp}$ discussed earlier. The reason for this is that the $E_{mnf}$ component of $E_{ctg}$ has been assumed to be unaffected by the use of recycled materials in batteries. Under current recycling schemes, this is a valid assumption.

The values shown in Figs. 3 and 4 for "virgin" PbA batteries are based on data from Table 7. Due to the maturity of its recycling infrastructure, they probably already reflect a substantial recycle content. On the other hand, if PbA batteries were made from purely virgin materials, we estimate their $E_{ctg}$ to be 35 MJ/kg instead of 29 MJ/kg found in the Table 7.

Based on average results from Table 7, Fig. 5 shows the relative contributions of $\langle E_{mp}\rangle$ and $\langle E_{mnf}\rangle$ to $\langle E_{ctg}\rangle$. Regarding the contributions of the two terms to $E_{ctg}$, it is evident from the figure that $E_{mp}$ share is about two thirds for PbA and Na/S, and a half for NiMH, Li-ion, and NiCd. Again, these trends must be considered provisional, given the variation of the data.

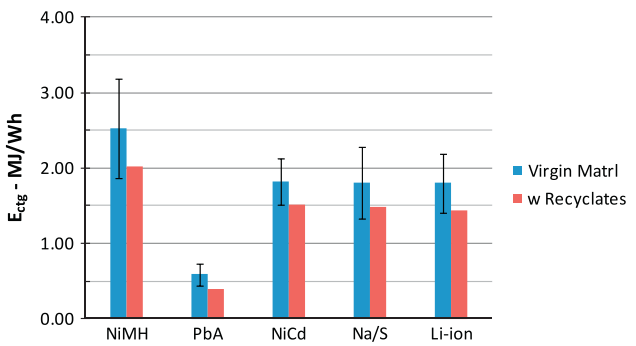



**Fig. 4.** $E_{ctg}$ values on a per Wh capacity basis ± one standard deviation for the various battery technologies; values based on averages in Table 2 and adjusted by specific energies given above.

## 5. Emissions

Thus far, our focus has been on $E_{ctg}$ analysis and its components. The literature has fewer life-cycle publications where emissions were 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. With the exception of one Ref. [1], combustion-related emissions ($CO_2$ and criteria pollutants) discussed here were either extracted directly from the cited Refs. [3,5–7] or computed from them using GREET 1.8 [28] and provided fuels data [4,9,25]. Although a few sources of process-specific emissions (air and water) have been included here [1,5,6], such data are typically less frequently reported in the open literature.

Emissions data are recorded in Tables A2 and A3, the latter of which records a very limited set for recycling operations. With the exception of Rantik [1], only those values that include both the material production and battery manufacturing stages are recorded.

Author's personal copy



### 5.1. Carbon dioxide emissions

Tables A2 and A3 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 [25]. Generally, GHG emissions per kilogram of battery are at most a few percent greater than direct $CO_2$ emissions.

To facilitate a comparison of the data, average *ctg* carbon dioxide emissions per kg of battery ($\langle CO_2 \rangle_{ctg}$) are presented in Fig. 6. As expected, the emissions levels among the technologies showed in the figure trend essentially the same way as those seen in Fig. 3. In summary, the ranked list of $CO_2$ emissions for the batteries 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.

The cradle to gate $CO_2$ values shown in Table A3 for Refs. [4,9] were calculated from their fuel data using GREET 1.8 [28]. Because the Hittman report [4] lists primary energy values by fuel type, those data were easily processed in GREET to yield emissions results. A similar approach was taken for Ref. [9]. In that case, using their reported electricity fraction of $E_{ctg}$ 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. All values listed in Tables A2 and A3 are based on virgin constituent materials, except for PbA batteries, which as a matter of practice already have a substantial recycled Pb content. The impact of material recycling on $CO_2$ emissions for battery production is anticipated to mirror the reductions discussed above for energy.

From energy consumption data given by Rantik [1], we also calculated a set of $CO_2$ emission values for battery recycling operations using GREET 2.7 [25]. Those values are shown in Table A3 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); 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. Due to an unspecified credit, values reported by Kertes [5] for battery recycling have not been included in the table.

### 5.2. Criteria pollutants

Tables A2 and A3 also list the CTG combustion-related criteria pollutants for the five batteries. 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. To facilitate comparison, these averages, which represent controlled emissions, are plotted in Fig. 7. It is clear from the figure that criteria pollutant emissions per kilogram of PbA battery are less than any of the other battery technologies. This trend is virtually the same when plotted on a per Wh basis.

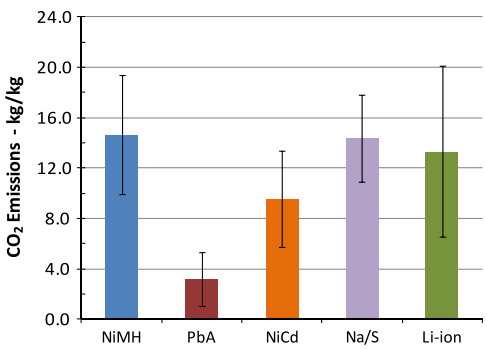



**Fig. 6.** Average CTG $CO_2$ emissions ± one standard deviation for the production of a kg of indicated batteries.

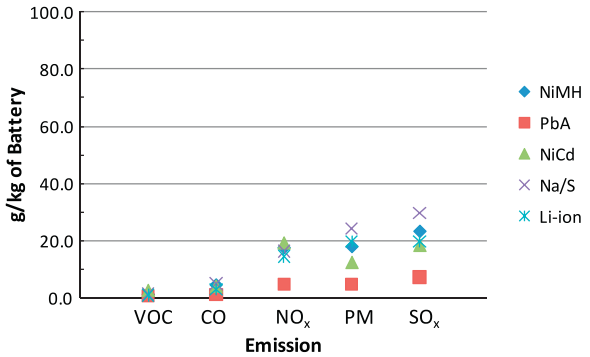



**Fig. 7.** Average criteria pollutant emissions (grams) per kilogram of battery for five batteries.

Also shown in Table A2 are several very large $SO_x$ emission values for NiMH and NiCd batteries. Because they are not combustion related emissions but instead are by-products of the smelting of sulfide ores, they have not been included in table averages. Though virgin Pb is also derived from a sulfide ores (mostly galena), we were unable to find a comparable emission value for PbA batteries. Generally, smelting related $SO_x$ is captured and subsequently used to make sulfuric acid and other products. We have no data on what fraction of $SO_x$ by-products is fugitive.

### 5.3. Other emissions

Process-specific air, water, and some solid waste emissions are also recorded in Tables A2 and A3. Given the industry and the materials being considered, these emission values are expectedly 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. For Table A2, the data attributed to Rantik [1] represent only the battery manufacturing stage, whereas those derived from Gaines et al. [6] represent only Ni production. The magnitude of the variation is considerable, ranging from one to more than two orders of magnitude. However, some of this variation is likely due to both location effects and evolving emission regulations. Nonetheless, better emissions data are clearly needed.

Note that the results given in Table A3 represent emissions related to recycling batteries and do not necessarily reflect the impact of using recycled materials in new batteries.

## 6. Battery recycling

PbA batteries are highly recycled — some estimate it to be around 95%. Currently, new PbA batteries range from 60% to 80% recycle content [18]. 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

Author's personal copy



made into sodium sulfate, which is in turn used for making detergents or other products. An alternative approach to recycling these batteries [5] is to simply smashed and feed unseparated batteries into a blast furnace to recover only molten lead. The battery plastic is used as both a fuel and reductant in the process.

Rantik [1] cites a value of 4.4 MJ/kg for recycling PbA batteries, a value taken from Kertes [5] for a smelting operation in Sweden. 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 corresponding values in Table A1.

Two literature references were found that cite $PE_j$ values for recycled Ni (see Table A1). However, as indicated in the table, little detail on processes and energy are available to judge its quality. In a proprietary study, Gaines et al. report another value, which is slightly lower than the value shown in the table. Unfortunately, that value is also supported by insufficient detail to judge its quality.

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 recovery of valuable metals (Co, Ni, Ti, Cd, Cu) that they contain. Today, the most used approach is pyrometallurgical. Using data from Schulter and Garcia [29], Rantik [1] estimates an energy requirement of 4.85 MJ to recycle a kilogram of NiCd batteries, yielding yield 0.246 kg and 0.703 kg of Cd and ferronickel, respectively. Though the ferronickel is not a material that is recycled back into batteries, it is 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. Unfortunately, mischmetal hydrides currently are not recovered. And as mentioned above for PbA battery recycling, polymer material may instead be used for part of the energy needed to power the recycling process.

A number of commercial approaches used to recycle batteries have been developed. A brief description of them can be found elsewhere [12]. 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 Umicore does not recover the Li at this time, they could do so in the future if lithium prices in the secondary market become sufficiently attractive. In fact, the battery recycling industry has concerns about the reduction of cobalt use in Li-ion batteries, since reduced yields of Co from the recycling stream could make their processes uneconomical. This could result in a fee for battery recycling. For Li-ion batteries, they are fed into a smelting furnace, where metals are recovered, and subsequently sent onto 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 significant 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 also 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, [12] has developed a process that recovers anode and cathode materials in a form that could potentially be reused in batteries. This effort is novel and unique, as it offers a way to reuse these valuable materials without taking them back to an elemental state. 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. Another advantage of both the OnTo and Toxco approaches is the avoidance of air and water emissions associated with winning these materials from earth.

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 processes for recycling sodium and sulfur from these batteries are apparently still not developed.

As indicated above, 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. With the exception of PbA batteries, Table A1 shows available LCI information on battery material recycling is spotty and lacks detail.

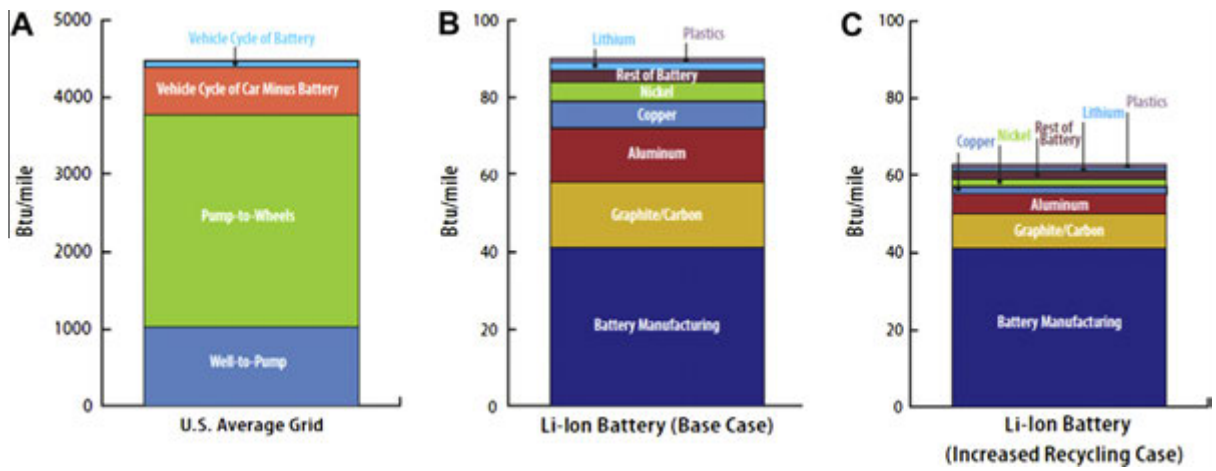



**Fig. 8.** Battery and vehicle life-cycle burdens.

Author's personal copy



## 7. Impact of battery *ctg* performance on application

While the cradle to gate energy and emission burdens of battery production are significant, the relative implications of those impacts on the life-cycle performance of a battery application can be quite small. This is particularly evident when Li-ion batteries are used for plug-in hybrid electric vehicles (PHEV) applications. As seen in Fig. 8, when a 85 kg battery is used for a PHEV-20 (20 mile all electric range) and driven 160,000 miles of lifetime driving distance, the contribution of the battery $E_{ctg}$ is small in comparison to the overall vehicle life-cycle energy.

If we assumed a 50% reduction in $E_{mp}$ for this battery, $E_{ctg}$ decreases by about 30%. However, when considered in the context of this application, one might be tempted to conclude that battery recycling is of little consequence. While this is true for $E_{ctg}$, other important reasons for making batteries from recycled materials

**Table A1**
Cradle-to-gate production energy values and an assessment of data detail for lead-acid battery materials; bold values used for $E_{mp}$ calculations.

| Material | Source | $PE_j$ (MJ/kg) | Energy detail[a] | Process detail[a] | Reference | When published |
|---|---|---|---|---|---|---|
| Pb | Ore | 22.3 | Y | Min | [25] | 2006 |
| Pb | **Ore** | **27.2** | **Y** | **Y** | **[4]** | **1980** |
| Pb | Ore | 28.7 | Y | Min | [30] | 1979 |
| Pb | Ore | 31.2 | Y | Y | [4] | 1980 |
| Pb | Scrap | 4.2 | Y | Min | [25] | 2006 |
| Pb | **Scrap** | **5.3** | **Y** | **Y** | **[2]** | **1995** |
| Pb | Scrap | 11.2 | Y | Y | [4] | 1980 |
| Pb | Scrap | 7.2 | N | N | [30] | 1979 |
| PbO | **Pb** | **12.7** | **Y** | **Y** | **[4]** | **1980** |
| Polypropylene | Petr./NG | 73.4 | Y | Y | [27] | 2005 |
| Polypropylene | Petr./NG | 75.5 | Y | Y | [31] | 2003 |
| Polypropylene | **Scrap** | **15.1** | **N** | **N** | **[2]** | **1995** |
| Sulfuric acid | **Ore** | **0.042** | **Y** | **Y** | **[4]** | **1975** |
| Glass fiber | Sand | 25.9 | Y | Y | [2] | 1995 |
| Cd | **Virgin** | **70** | **N** | **N** | **[32]** | **1999** |
| Cd | **Scrap** | **38** | **N** | **N** | **[11]** | **2002** |
| Ni | **Ore** | **224** | **Y** | **Y** | **[1]** | **2007** |
| Ni | Ore | 148 | Y | Y | [22] | 2006 |
| Ni | Ore | 186 | N | N | [6] | 2002 |
| Ni | Ore | 122 | N | Y | [2] | 1995 |
| Ni | Scrap | 37 | Min | Min | [25] | 2006 |
| Ni | Scrap | 40 | N | N | [11] | 2002 |
| $Ni(OH)_2$ | **Ore** | **193** | **Y** | **Y** | [4] | **1980** |
| $Ni(OH)_2$ | Ni | 33 | Y | Min | [25] | 2006 |
| $Ni(OH)_2$ | Ni | 76.7 | N | N | [2] | 1995 |
| $Ni(OH)_2$ | Ni | 26 | Y | Y | [4] | 1980 |
| $Ni(OH)_2$ | **Scrap** | **63**[b] | **N** | **N** | [4] | **1980** |
| KOH | Ore | 10.8 | N | N | [2] | 1995 |
| KOH | **Ore** | **38.2** | **Y** | **Y** | [4] | **1975** |
| Mischmetal | Ore | 681[c] | Y | Y | [3] | 1999 |
| Mischmetal | **?** | **116** | **N** | **N** | [2] | **1995** |
| Steel | **Ore** | **37.2** | **Y** | **Y** | [25] | 2006 |
| Steel | **Scrap** | **8.3** | **Y** | **N** | [25] | 2006 |
| Nylon | **Petr/NG** | **120** | **Y** | **Y** | [27] | **2005** |
| Co[d] | **Ore** | **144** | **Y** | **Y** | [4] | 1980 |
| Co[d] | **Scrap** | **43** | **N** | **N** | Estimate | |
| $Li_2CO_3$ | Brines | 32.2 | Y | Y | [7] | 2010 |
| $Li_2CO_3$ | **Brines** | **43.8**[e] | **Y** | **Y** | [33] | **2009** |
| $LiOH–H_2O$ | Ore | 163 | Y | Y | [4] | 1980 |
| LiCl | Ore | 220 | Y | Y | [4] | 1980 |
| $LiNiO_2$ | Ore | 65.1 | N | N | [3] | 1999 |
| $LiPF_6$ | | 184 | N | N | [3] | 1999 |
| Graphite | Ore | 51.7 | Y | Y | [7] | 2010 |
| Graphite | Coke | 202[g] | N | N | [25] | 2006 |
| Graphite | **Pet. Coke** | **187** | **Y** | **Y** | [4] | **1980** |
| Ethylene carbonate | | **32.4**[h] | **Y** | **Y** | [7,31] | 2010 |
| $LiMn_2O_4$ | Ore | 34.6[i] | Y | Y | [31] | 2010 |
| Al | **Ore** | **204** | **Y** | **Y** | [25] | **2006** |
| Al | **Scrap** | **31.8** | **Y** | **Y** | [25] | **2006** |
| Copper | **Ore** | **111** | **Y** | **Y** | [25] | 2006 |

(*continued on next page*)

Author's personal copy



**Table A1** (*continued*)

| Material | Source | $PE_j$ (MJ/kg) | Energy detail[a] | Process detail[a] | Reference | When published |
|---|---|---|---|---|---|---|
| Sodium | Salt | 165 | Y | N | **[30]** | 1979 |
| Sodium | **Salt** | **107** | **Y** | **Y** | [4] | 1980 |
| Sulfur | **Deposits** | **6.7** | **Y** | **N** | **[30]** | **1979** |
| Sulfur | Deposits | 2.3 | Y | Y | [4] | 1980 |
| β-Alumina | **Bauxite** | **196–635** | **Min** | **Min** | **[2]** | **1995** |
| β-Alumina | Bauxite | 1189 | Y | Y | [4] | 1980 |

[f] Calculated from data in reference; data represent a South American (Atacama) location.
[a] Y = yes; N = no; Min = minimal.
[b] Estimated as the sum of scrap to Ni and Ni to Ni(OH)2.
[c] Inferred from their Tables 4 and 6.
[d] A co-precipitation process yielding Co as byproduct of nickel and copper production.
[e] Data representing a North American production operation; co-product allocation not available.
[g] Surrogate representation; carbon fiber production.
[h] Estimated using ethylene and ethylene oxide data from USLCI data base and ethylene carbonate data from Notter.

**Table A2**
Air, water, and solid wastes for cradle-to-gate battery production (g/kg of battery, unless otherwise stated); bold values are for manufacturing only; average values for cradle to gate only.

| Technology | VOC (g/kg) | CO (kg/kg) | $NO_x$ (mg/kg) | PM | $SO_x$ | $CH_4$ | $N_2O$ | $CO_2$ | Water (mg/kg) | Air (mg/kg) | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 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*** | **1**[a] | |
| | 4.2 | 2.51 | 25.4 | 2.2 | 23.9 | 0 | 0.01 | 4.15 | 47 – Heavy metals | 316 - hvy metals | [5][d] |
| | 1.3 | 4.5 | 27 | 2.8 | 263[f] | 22.7 | 0.19 | 14.8 | *18*[b] *– heavy metals* | 100[b] – heavy metals | [6] |
| | | | 19 | | 14 | | | 15 | | | [3] |
| | 0.7 | 2.1 | 8.7 | 14.0 | 19.2 | 11.1 | 0.11 | 8.3 | | | [25] |
| | 0.9 | 3.9 | 11.4 | 18.9 | 20.5 | 15.3 | 0.1 | 10.3 | | | [9][c] |
| | 1.8 | 7.5 | 21.8 | 36.1 | 38.9 | 29.3 | 0.3 | 19.5 | | | [9][c] |
| Average | 1.2 | 4.5 | 17.6 | 18.0 | 23.3 | 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** | **[1]**[a] |
| | 2.2 | 1.3 | 7.9 | .8 | 10.3 | .002 | 0.006 | 1.1 | *97 – Heavy metals* | 118 – Heavy metals | [5] |
| | | | 5.8 | | 5.3 | | | 5.1 | | | [3] |
| | 0.57 | 1.65 | 6.8 | 11.0 | 14.9 | 8.7 | .09 | 6.4 | | | [25] |
| | 0.2 | 0.9 | 2.1 | 2.6 | 2.8 | 3.4 | 0.02 | 1.9 | | | [4] |
| | 0.2 | 0.7 | 2.1 | 3.5 | 3.7 | 2.9 | 0.0 | 1.9 | | | [9][c] |
| | 0.3 | 1.2 | 3.5 | 5.7 | 6.0 | 4.6 | 0.0 | 3.1 | | | [9][c] |
| Average | 0.7 | 1.1 | 4.7 | 4.7 | 7.2 | 3.9 | 0.0 | 3.2 | | | |
| NiCd | | | | | | | | | **60 – Cd, Co, Ni** | **40 – Cd, Co, Ni** | **[1]**[a] |
| | 5.9 | 5.4 | 40 | 5.2 | 20.5[e] | 0.001 | 0.015 | 6.2 | 30 – heavy metals | 740 – heavy metals | [5] |
| | | | 17.4 | | 167[f] | | | 14.8 | | | [11] |
| | 0.7 | 2.8 | 8.1 | 13.4 | 14.5 | 10.9 | 0.1 | 7.3 | | | [9][c] |
| | 0.9 | 3.8 | 11.1 | 18.3 | 19.8 | 14.9 | 0.1 | 9.9 | | | [9][c] |
| Average | 2.5 | 4.0 | 19.2 | 12.3 | 18.3 | 8.6 | 0.1 | 9.6 | | | |
| Na/S | 1.7 | 5.7 | 21.2 | 27.1 | 38.8 | 27.8 | 0.24 | 18.7 | | | [4] |
| | 1.1 | 4.4 | 13.0 | 21.4 | 23.4 | 17.3 | 0.2 | 11.6 | | | [9][c] |
| | 1.2 | 4.9 | 14.6 | 24.2 | 26.5 | 19.6 | 0.2 | 13.2 | | | [9][c] |
| Average | 1.3 | 4.9 | 16.0 | 23.7 | 29.3 | 21.4 | 0.2 | 14.3 | | | |
| Li-ion | | | 22.5 | | 17.5 | | | 18.2 | | | **[3]** |
| NCA | | | | | | | | 7.0 | | | [24] |
| LMO | | | | | | | | 7.2 | | | [24] |
| | 0.6 | 1.8 | 7.6 | 17.3 | 16.7 | 9.7 | 0.1 | 7.2 | | | [25] |
| NCA | 1.1 | 4.3 | 13.3 | 21.9 | 24.9 | 17.6 | 0.2 | 12.1 | | | [9][c] |
| NCA | 1.7 | 6.4 | 20.0 | 32.9 | 37.4 | 26.5 | 0.2 | 18.1 | | | [9][c] |
| LMO | | | | | | | | 6.0 | | | [7] |
| Average | 0.9 | 3.0 | 14.5 | 19.6 | 19.7 | 13.7 | 0.1 | 10.8 | | | |

[a] Does not include battery material production; values derived from references cited therein.
[b] Solely from Ni production; assumed battery is 25% Ni.
[c] Used the max and min of the total energy values cited in Table 7.
[d] Mischmetal hydride production and Ni mining not included; hence not a part of table averages.
[e] Value is 265 when $SO_4$ by product is included.
[f] Includes $SO_2$ from smelting and hence not included in the average.

Author's personal copy



**Table A3**
Emissions to air, water, and solids for battery recycling (g/kg battery, unless otherwise stated).

| Technology | VOC (g/kg) | CO (kg/kg) | $NO_x$ (mg/kg) | PM | $SO_x$ | $CH_4$ | $N_2O$ | $CO_2$ | Water (mg/kg) | Air (mg/kg) | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 | | 1[a] |
| 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 | 1[a] |
| 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 | 1[a] |

[a] Values attributed to Rantik derived from references cited therein.

like Ni and Co include: (1) conservation of relatively scarce or expensive materials, and (2) reduction of material production emissions like $SO_x$ when these materials are won from earth.

## 8. Conclusion

A review was conducted of the cradle to gate production energy and emissions for five battery technologies. They are: lead-acid, nickel–cadmium, nickel-metal hydride, sodium-sulfur, and lithium-ion batteries. Included in the review was an analysis of energy and emissions of the two life-cycle stages that comprise cradle to gate production, namely battery material production and battery manufacturing. For the former stage, a wide range of battery material production energy values can be found in the literature for each technology. A number of factors were identified that contribute to the range, including study to study variation in battery composition, mass accounted for, constituent material production energies, boundary blur, and finally recycle content.

Based on battery composition and published constituent material production energies, estimates were made for the battery material production energy. For batteries made from virgin materials, our estimates generally fall within the range identified from the literature. Nonetheless, given the width of the range for each technology, the accuracy of our battery material production estimates are not known. Though our estimate for lead acid batteries is expected to be quite representative given that most of their constituent material production energies are well known, this is not the case for the other batteries. Indeed, material production energies are needed for many battery constituent materials including Co, $LiCoO_2$, $LiMn_2O_4$, $LiNiO_2$, $LiFePO_4$, $LiCo_{1/3}$, $Ni_{1/3}Mn_{1/3}O_2$, graphite ($LiC_6$), $LiPF_6$, $LiBF_4$, $LiClO_4$, diethyl carbonate, and ethylene carbonate for lithium ion batteries, Cd for nickel cadmium batteries, β-alumina for sodium sulfur batteries, and mischmetal hydrides for nickel metal hydride batteries.

For batteries made from recycled materials, our material production energy estimates are typically higher. This is due to the lack of material production data for many battery materials, thus highlighting the need for life-cycle data in this area. The materials where such data is needed have just been listed above. Given the lack of energy detail for many battery materials derived from recycled sources, the corresponding material production stage for batteries are likely optimistic.

More data is also needed on the manufacturing processes required to make and assemble batteries from their constituent materials. Unfortunately, only a limited set of published energy values for the manufacturing stage of the batteries can be found in the literature, and like their material production counterparts, they also range considerably.

Though published cradle to gate battery production energy values vary widely due to variation in material production and manufacturing energies, some useful trends have been shown. Per kilogram of battery, the cradle to gate production energy of PbA batteries is the lowest of the five batteries reviewed, NiCd is the next lowest, with the remaining batteries sensibly tied, given the variation in results. Another observed trend is that battery manufacturing and assembly energy is about a third of the cradle to gate value for PbA and Na/S batteries, and about half for NiCd, NiMH, and Li-ion batteries.

When cradle to gate $CO_2$ are ranked across battery technologies, the trend among the batteries is effectively the same as that observed for energy. And when cradle to gate battery production air emissions are compared, PbA has the lowest for all criteria pollutants, and the other batteries have a mixed ranking over the five pollutants. Though the production of battery materials like lead, nickel, cobalt, and cadmium generate significant $SO_x$ by-products, with the exception of fugitive emissions are made into products like sulfuric acid.

## Appendix A

See Tables A1–A3.

## References


[1] Rantik M. Life cycle assessment of five batteries for electric vehicles under different charging regimes, ISSN 1401-1271. Goteborg, Sweden: Chalmers University of Technology; 1999.
[2] Gaines L, Singh M. Energy and environmental impacts of electric vehicle battery production and recycling, SAE Paper 951865; 1995.
[3] Ishihara K, Nishimura K, Uchiyama Y. Life cycle analysis of electric vehicles with advanced battery in Japan. In: Proceedings of the electric vehicle symposium, vol. 16, Beijing, China; 1999. p. 7.
[4] Hittman Associates. Life cycle energy analysis of electric vehicle storage batteries, H-1008/001-80-964, submitted to the US Department of Energy, contract number DE-AC02-79ET25420.A000; 1980.
[5] Kertes A. Life cycle assessment of three available battery technologies for electric vehicles in a Swedish perspective. Masters thesis, Stockholm, Sweden: Royal Institute of Technology; 1996.
[6] Gaines L, Elcock D, Singh M. Nickel-metal hydride batteries: energy use and emissions from production and recycling, SAE Paper 02FCC-49; 2002.
[7] Notter DA, Gauch M, Widmer R, Wager P, Stamp A, Zah R, et al. Contribution of Li-ion batteries to the environmental impact of electric vehicles. Environ Sci Technol 2010;44:6550–6.
[8] Majeau-Bettez G, Hawkins TR, Hammer Strømman A. Life cycle environmental assessment of lithium-ion and nickel metal hydride Batteries for plug-in hybrid and battery electric vehicles. Environ Sci Technol, web, 4/20/11.
[9] Rydh CJ, Sanden BA. Energy analysis of batteries in photovoltaic systems — Part I: performance and energy requirements. Energy Convers Manage 2005;46:1957–79.
[10] Rydh CJ, Sanden BA. Energy analysis of batteries in photovoltaic systems — Part II: energy return factors and overall battery efficiencies. Energy Convers Manage 2005;46:1980–2000.
[11] Rydh CJ, Karlstrom M. Life cycle inventory of recycling portable nickel–cadmium batteries. Resour Conserv Recy 2002;34:289–309.
[12] Gaines L, Sullivan J, Burnham A, Belharouak I. Life-cycle analysis for lithium-ion battery production and recycling. TRB 2011, Washington DC, Paper # 11-3891; 2011.
[13] ISO. ISO International Standard, ISO 14042. Environmental management — life cycle assessment — life cycle impact assessment; 2000.
[14] ISO, ISO International Standard, ISO 14041. Environmental management — life cycle assessment — goal and scope definition and Inventory analysis; 1998.
[15] ISO, ISO International Standard, ISO 14040. Environmental management — life cycle assessment — principles and framework; 1997.
[16] Protoscar Lampo (pure battery EV): specifications. <http://www.protoscar.com/pdf/LAMPO2/LAMPO2_Technical_Specifications.pdf> [accessed 29.08.11].
[17] MSDS, East Penn Manufacturing, Inc. <http://www.google.com/#hl=en&cp=20&gs_id=2t&xhr=t&q=lead±acid±battery±msds&pf=p&sclient=psy&source=hp&pbx=1&oq=lead±acid±battery±ms&aq=0&aqi=g1g-v2g-m2&aql=&gs_sm=&gs_upl=&bav=on.2,or.r_gc.r_pw.&fp=10c1846e50133d80&biw=1087&bih=593> [accessed 20.10.10].
[18] Battery Council International. Battery Council International website; 2010. <http://www.batterycouncil.org/LeadAcidBatteries/BatteryRecycling/tabid/71/Default.aspx>.

Author's personal copy



[19] Sullivan JL, Hu J. Life cycle energy analysis for vehicles. In: Proceeding of the 1995 total life cycle meeting, SAE technical paper 951829; 1995.
[20] EVTECA. Total energy cycle assessment of electric and conventional vehicles: an energy and environmental analysis, ANL/ES/RP–96387, provided by Argonne National Laboratory, National Renewable Energy Laboratory, and Pacific Northwest National Laboratory for the US Department of Energy; 1998.
[21] Plastics Europe. Increased resource efficiency; 2005. <http://www.plastics-europe.org> [accessed 27.08.11].
[22] Nickel Institute. Nickel Institute website; 2007. http://www.nickelinstitute.org/index.cfm?ci_id=15794&la_id= [accessed 20.09.10].
[23] Ananth MV et al. Influence of earth content on electrode kinetics in misch metal-based AB5 MH alloys — cyclic voltammetric investigations. Int J Hydrogen Energy 2009;34:356–62.
[24] Ishihara K, Kihira N, Terada N, Iwahori T. Environmental burdens of large lithium-ion batteries developed in a Japanese national project. <http://www.electrochem.org/dl/ma/202/pdfs/0068.PDF> [accessed 15.08.10].
[25] Burnham A, Wang M, Wu Yi. Development and application of GREET 2.7 – the transportation cycle model, ANL/ESD/06-5 and GREET 2.7. <http://www.transportation.anl.gov/modeling_simulation/GREET/index.htm> [accessed 14.06.10].
[26] Gaines L, Cuenca R. Costs of lithium-ion batteries for vehicles, argonne technical report, ANL/ESD-42. Argonne, IL: Argonne National Laboratory; 2000.
[27] Plastics Europe. Ecoprofiles; 2005. <http://www.plasticseurope.org> [accessed 07.12.10].
[28] GREET 1.8; 2010. http://www.transportation.anl.gov/modeling simulation/GREET/index.htm [accessed 04.04.11].
[29] Schulter F, Garcia A. Life cycle assessment of batteries for electric vehicles, MoP thesis 96:11. Goteborg, Sweden: Chalmers University of Technology; 1996.
[30] Boustead I, Hancock GF. Handbook of industrial energy analysis. New York: John Wiley & Sons, Inc.; 1979.
[31] US LCI Database. <http://www.nrel.gov/lci/database> [accessed 05.12.10].
[32] Boustead I, Dove WT, Halada K, Matsuno Y. Primary metal industry ecoprofile calculations: a discussion of allocation methods. In: Proceedings of the fourth international conference on ecomaterials, Gifu, Japan, 10th–12th, pp. 315–8. <http://www.boustead-consulting.co.uk/publicat.htm> [accessed 15.10.10].
[33] Argonne National Laboratory data.