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Energy and Environmental Impacts of Electric Vehicle Battery Production and Recycling

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ABSTRACT

Electric vehicle batteries use energy and generate environmental residuals when they are produced and recycled. This study estimates, for four selected battery types (advanced lead-acid, sodium-sulfur, nickel-cadmium, and nickel-metal hydride), the impacts of production and recycling of the materials used in electric vehicle batteries. These impacts are compared, with special attention to the locations of the emissions. It is found that the choice among batteries for electric vehicles involves tradeoffs among impacts. For example, although the nickel-cadmium and nickel-metal hydride batteries are similar, energy requirements for production of the cadmium electrodes may be higher than those for the metal hydride electrodes, but the latter may be more difficult to recycle.

INTRODUCTION

The U.S. Department of Energy (DOE) is conducting a total energy cycle assessment (TECA) of electric vehicles (EVs). The purpose is to prepare an energy and emissions inventory for EVs and to compare that inventory with one for conventional vehicles. Such a comparison will allow DOE to evaluate EV technology and address potential environmental problems. Work is being carried out at Argonne National Laboratory, Pacific Northwest Laboratory, and the National Renewable Energy Laboratory. The work we describe here is part of the EVTECA study.

Although much has been written about the performance characteristics of batteries for EVs, information about materials and the production and recycling processes is not readily available. Such information has not been the primary focus of interest, the designs and processes are still in flux, and much of the information is proprietary. However, studies of health and environmental effects provide some data on battery materials and their handling. This paper summarizes available information on the materials in four types of advanced electric vehicle batteries: advanced lead-acid (Pb-acid), sodium-sulfur (Na-S), nickel-cadmium (Ni-Cd), and nickel-metal hydride (Ni-MH).

Certain insights about battery materials apply to all four types, to varying degrees. First, and most obviously, the batteries will make up a significant fraction of the vehicle mass (~20-40%). The impacts are magnified by the fact that some of the batteries are expected to have shorter lifetimes than the vehicles and will therefore need to be replaced at least once. Another insight is that some thought is going into battery recyclability at the design stage because the electric vehicle is being "born green." In contrast to the small consumer cells now simply being chopped up, EV batteries will be large enough to warrant consideration of disassembly and material segregation (manual or automated) as the first step in recycling. However, work on appropriate methods for reclaiming some of the materials is at best incomplete.

Another insight concerns the materials mixes in advanced batteries. The electrode and electrolyte materials for all types, except Pb-acid, are nonstandard automobile materials (although some cadmium has been used in coatings and pigments), for which little process information is readily available. However, a significant fraction of the battery mass is made up by casings, separators, and connectors, which are generally made of more common materials like steel and polypropylene. These are well-characterized, so the uncertainty about impacts from the batteries is reduced.

Production of materials for batteries generates process emissions, from physical and chemical processes carried out on the materials, and emissions from combustion of fuels to drive these processes. The process emissions, which differ for each material, are discussed below in sections about specific materials. The emissions from fuel combustion, which are standard combustion products, are put in perspective in a later section that compares the emissions from energy use for material production with those produced by the car over its lifetime.

ADVANCED LEAD-ACID BATTERIES

Lead-acid batteries are used in automotive electrical systems, and some information about their production is available. They are also recycled commercially. The production and recycling processes for materials in conventional lead-acid batteries can be used with minimal changes for advanced EV batteries. Therefore, materials, energy use, and emissions from the manufacture and recycling of these batteries can be estimated.

The battery lifetime is up to 80,000 miles, so one replacement would generally be necessary over an EV's lifetime. [1]

BATTERY DESIGN- The Horizon EV battery, developed by Electrosource (Austin, Texas) and BDM Technologies, is an advanced lead-acid battery slated to begin limited commercial production in 1995. This battery has an energy density of over 45 Wh/kg. It uses electrodes produced by co-extruding "an alloy of lead onto a high tensile strength core material, making a small diameter, dimensionally stable wire that is woven into lightweight bipolar mesh grids." [2] The core can be graphite or fiberglass. [1] The electrodes are then coated with a proprietary paste and assembled horizontally into batteries. The paste is reportedly made from refined lead dust and dilute sulfuric acid. For the negative electrodes, a small amount (~1%) of carbon black, barium sulfate, and lignin-sulfonate is added. For the positive, about 0.03% of a polymer, such as polypropylene (PP), or possibly glass fiber, is added. [3] Fiberglass mats between the porous electrodes separate them and hold the acid electrolyte, which is all absorbed in the mats and electrodes.

The manufacturing equipment for these batteries is being developed, but the infrastructure already in-place can be used to recycle them. Over 98% of spent auto batteries in the U.S. are currently recycled. [4]

BATTERY MATERIALS- Because even advanced Pb-acid batteries have the lowest energy density of the batteries considered, they use the largest mass of materials. At 50 Wh/kg, a 25-kWh battery module would weigh 500 kg (1100 lb). The materials inside advanced lead-acid batteries are lead, lead oxide, acid, and fiberglass mats. The containers/covers are generally PP, but steel can also be used. Aluminum trays were considered, but lightweight steel was determined to be cheaper.

Lead- Energy required to produce primary lead was earlier estimated to be roughly 23.4 x 10^6 Btu/ton. [5] (Note: 10^6 Btu/ton = 1.16 MJ/kg.) The same source estimated secondary lead production to require 9.5 x 10^6 Btu/ton, compared to a more recent estimate of 4.6 x 10^6 Btu/ton for the smelting step alone at a modern smelter. [6] We expect that primary production energy also has been reduced.

Primary lead is produced from sulfide ores by sintering, reduction in a blast furnace, and refining to 99.99+% purity. As is typical for smelting of sulfide ores, the primary effluent is SO_2, nearly 85% of which is produced during sintering. Half of the remainder is captured in the slag; most of the rest is recovered from the blast furnace. Most of the impurities are entrained in the slag. In addition, lead compounds, such as oxides, are released as particulates during both primary and secondary (recycling) lead smelting operations, and during battery manufacture and recycling. Sulfur oxides and lead are both serious health and environmental concerns; regulations in the U.S. have generally resulted in careful control of these emissions. (The EPA has forced older plants not meeting these standards to close.) Particulates are usually controlled with a baghouse, with control efficiencies exceeding 99%. Sulfur dioxide is recovered and converted to sulfuric acid (see next section). Emission factors reported for primary lead smelting are lead, 0.034 kg/tonne (0.07 lb/t), and uncontrolled SO_2, 23 kg/tonne (45 lb/t). Controlled lead emissions from secondary smelting are approximately 0.15 kg/tonne (0.29 lb/t), and uncontrolled SO_2 emissions, 40 kg/tonne (80 lb/t), but these values are based on very limited data. [7] Fugitive emissions may be somewhat higher; no actual data are available. The fuel/reductant in the blast furnace is metallurgical coke (8-14% of the charge); emissions from coke production are not discussed here but will be included in the EVTECA.

Primary lead production in the U.S. is concentrated in Missouri, which accounts for 75% of production. Secondary smelting and battery recycling are more geographically spread and more likely to occur near population centers. Solid wastes generated from mining operations remain in somewhat remote locations. Slag produced during smelting is a relatively inert solid that is generally disposed of.

Sulfuric Acid- The electrolyte in lead-acid batteries is 22-26% sulfuric acid (H_2SO_4), generally made by combustion of sulfur to sulfur dioxide (SO_2), further oxidation to sulfur trioxide using a vanadium-based catalyst, and absorption into strong sulfuric acid followed by dilution to the desired concentration. Most elemental sulfur in the U.S. is a by-product of oil and gas extraction; its production is described below. Alternatively, by-product SO_2 from smelting of sulfide ores (e.g., lead sulfide) can be the raw material. In either case, the reactions are highly exothermic, and fuel purchases are generally not required (except small quantities of natural gas during startup).

The tail gas from the final absorption tower may contain small quantities of SO_2, and even smaller quantities of SO_3. Older single-absorption plants can achieve SO_2 emission levels of 27 lb/t H_2SO_4 (97.9% conversion), and newer dual-absorption plants can meet the 4-lb/ton NSPS (99.7% conversion). H_2SO_4 mist from the stack is generally controlled by demister pads or mist eliminators that reduce emissions by more than 95%. [8]

Sulfuric acid is generally produced where metals are smelted from sulfide ores, well outside population centers. Acid mist is also produced during battery-breaking (recycling), a more geographically widespread process.

Polypropylene- Polypropylene is a polymer of the organic chemical propylene (C_3H_6), a co-product of ethylene manufacture from natural gas liquids or petroleum. Energy required for PP production is approximately 68 X 10^6 Btu/ton, mostly in the form of oil and gas. [9] Recycling simply requires remelting at low temperatures, and therefore requires considerably less energy, on the order of 13 x 10^6 Btu/ ton.

Emissions from propylene polymerization, shown in Table 1, are in the form of particulates (polymer resin) and gases (mostly the propylene monomer). Pollution control is via the systems for recovery of reactants or products. [7] Emissions from the entire PP production chain (not included here) occur at petroleum refineries or natural gas processing plants and at large chemical-production complexes. These facilities are located outside of major population centers, being concentrated on the Texas Gulf Coast, with a few scattered elsewhere in the United States.

Table 1- Emissions from Propylene Polymerization (Sources: [7] [8])

	Uncontrolled		Controlled	
Emission	kg/tonne	lb/t	kg/tonne	lb/t
Gas	0.35	0.7	0.19	0.4
Particulate	1.5	3.0	0.02	0.4
Solid (catalyst and treatment beds)	<0.1	<0.2	<0.1	<0.2

Fiberglass- The production of fiberglass is very similar to that of container or float glass (sheet), except for the final fabrication step. The raw materials (mainly sand, limestone, and soda ash) are transported to a plant, where they are melted at high temperature and then formed into fibers. Energy required to produce fiberglass, including energy to produce and transport the chemical inputs, is estimated to be 22.3 × 10^6 Btu/ton, mostly in the form of natural gas. Energy to recycle would be somewhat lower, about 18.9 × 10^6 Btu/ton, but it is not clear that sufficiently clean material could be separated from battery scrap.

Fugitive dust and raw-material particles from raw-material handling are controlled by moist handling or by fabric filters on enclosed transfer points. Emissions from melting and refining may include volatile organics, raw-material particles, and combustion gases; these are controlled by fabric filters. Particulates are the main emissions from fiber-forming. Particulate emissions are common to all glass manufacture; boron and fluoride emissions result from the special chemical composition of fiberglass.

RECYCLING PATHS- The electrode grids from spent lead-acid batteries are often corroded and stretched out so that electrical contact is reduced or lost. Lead sulfate is formed in crystals large enough that they do not reconvert during charging. Therefore, the battery components cannot simply be reused; they must be reprocessed. [10] Currently, over 90% of the lead and lead oxides from batteries is recycled or exported for recycling. These materials are processed by secondary lead smelters, which provide about 2/3 of the U.S. lead supply, but some uses require the purer primary product. Approximately 80% of secondary lead is used to produce new automotive batteries. Currently, the price of imported lead is low, presenting an incentive to import lead and export scrap instead of recycling it in the U.S. If scrap is exported to Asia, smelters operating there with less stringent (or no) pollution-control regulations could have an economic advantage and cause severe health effects. Another barrier to increased lead recycling is that secondary slag is categorized as hazardous by the EPA, but primary slag, chemically the same material, is not. Transportation and recycling of spent lead-acid batteries is also regulated. This is typical of the U.S. regulatory system.

In an operating lead-acid-battery recycling plant, the batteries are dismantled mechanically. The top of the battery is sheared off and the acid drained. The lead is separated out as metallic, oxide, and sulfate fractions and recycled to new electrodes. The casings and plate separators are segregated; the PP case fragments are recovered by a sink/float process and recycled to new battery cases or other products, like plastic piping. The acid is cleaned by solvent extraction and reused, or it can be used to neutralize KOH or to make sodium sulfate crystals for soap manufacture. The glass mats from advanced lead-acid batteries reportedly can be recycled. Plant emissions are controlled to meet EPA and OSHA regulations; the plant discharge contains less than 200 ppm SO_2. [6]

Processes to recover lead from the sulfates (and reduce sulfur emissions) are under development by the U.S. Bureau of Mines. Paste containing lead sulfate and lead oxide can be desulfurized with soda ash to produce marketable sodium sulfate; the desulfurized paste can then be processed in a reverberatory furnace or electrowon. Electrowinning could be used to improve lead recovery rates and produce a higher-purity product. R&D on this process is ongoing; recent papers include detailed process descriptions and estimates of energy use for secondary lead recovery by electrowinning. The energy required is approximately 6.7 × 10^6 Btu/ton, somewhat higher than that required by secondary smelting. [11] However, this process recovers material not easily treated in a secondary smelter. Lead emissions from pyrometallurgical processes are likely to exceed those from hydrometallurgical processes.

SODIUM-SULFUR BATTERIES

The Ford Ecostar is projected to use the Na-S type of battery, and the Audi Quattro will use it as part of its hybrid design. A noteworthy feature of the Na-S battery is that it operates at high temperature (at least 300-350°C), and the temperature must be maintained by insulation or heating from an outside source if the battery is not used daily. The battery is targeted for a 1000-cycle life, so that it would not require replacement over the vehicle life.

BATTERY DESIGN- The positive electrode is made of molten sulfur (graphite felt impregnated with S), and the negative electrode is molten sodium. Sodium is extremely reactive, and containing the materials is a crucial element of the battery design. Safety and regulatory issues are discussed in a recent series of reports by NREL. [12] [13]

The battery consists of multiple cells. Each contains a solid ceramic beta-alumina electrolyte, produced by electrophoretic deposition or isostatic pressing; this is sealed to an alpha-alumina component that insulates, with a glass seal on the electrolyte tube. The individual cells are housed in cylindrical metallic cell casings (Al or steel tubes), arranged in an array, with as many as 2000 in a double-wall thermal vacuum box. Banks of cells may be connected by mild steel plates.

BATTERY MATERIALS- The energy density in batteries of this type is estimated to be 80-200 Wh/kg, or about four times that of conventional Pb-acid batteries, so they are relatively lightweight. The specific energy of the cells themselves may be even higher (up to the theoretical 760 Wh/kg), but the thermal enclosure adds considerable mass. At 100 Wh/kg, a 25-kWh battery pack would weigh 250 kg (550 lb). The materials used include low-carbon steel, aluminum, stainless steel, copper, ceramics, sodium, sodium polysulfides, chromium, sulfur, alumina, and graphite. NREL estimates ~40 kg Na and 60 kg S for a 50-kWh battery. [13] Another estimate puts the relative masses at ~12% S, 6% Na, and 20% ceramics, with most of the remainder steel. [14]

Because of the high temperatures, plastics cannot be used for the cell casings. The housing, with modules placed in steel or aluminum outer double-wall, evacuated cylindrical containers, represents a large fraction of the total battery weight. One source describes the thermal enclosure as having a wall spacing of 2.54 cm, with 0.25-mm stainless steel sheets separated by fiberglass insulation board. [15] Other separators are possible.

Sodium- Sodium is produced by electrolysis of a fused mixture of NaCl and $CaCl_2$, with chlorine as the co-product. An early study for the U.S. Bureau of Mines estimated energy requirements for metallic sodium production at 92×10^6 Btu/ton, mostly in the form of electricity. [16] This estimate is in the middle of a very wide range cited more recently in a book that points out the uncertainty caused by allocation of energy to the co-products sodium and chlorine. [17]

Chlor-alkali plants may use flowing mercury (Hg) as the negative terminal; significant Hg losses were common until the advent of EPA regulations. Emissions are controlled to under 0.28 g/tonne of product by elaborate filtration systems and coolers to condense vapors.

Sulfur- About 63% of the elemental sulfur consumed in the U.S. is recovered as a by-product from processing crude oil or natural gas, concentrated on the U.S. Gulf Coast; the rest is mined or imported. Sulfur recovery actually has a positive impact on air quality, since the sulfur would otherwise be destined to become emissions. The sulfur in natural gas is generally in the form of hydrogen sulfide (H_2S), while that in crude oil is in a large variety of compounds that are converted to H_2S during processing. There are three process steps in sulfur production: amine scrubbing to remove H_2S from product streams, conversion by the Claus process to elemental sulfur, and tail-gas cleaning. All of the chemical reactions involved are exothermic; it is therefore believed that little, if any, purchased energy is required. An earlier researcher cited an estimate of 0.8×10^6 Btu/ton, which is indeed small. [5] The conversion to elemental sulfur does not go to completion; it leaves tail gas containing 0.8-1.5% sulfur compounds, necessitating tail-gas cleaning. Output gas from tail-gas cleanup is typically 50-250 ppm sulfur compounds; newer plants generally achieve under 40 ppm. The EPA limit is 250 ppm.

Beta-Alumina Electrolyte- The material used in the electrolyte is a ceramic in the sodium aluminate class, $Na_2O \cdot XAl_2O_3$, where the value of X may vary from 5 to 11 for the different compounds under consideration. The first few process steps, mining of bauxite, refining, and production of alumina, are similar to those used for production of primary aluminum. Energy to produce alumina is approximately 12.2×10^6 Btu/ton. High-purity raw material produces electrolyte with the most desirable properties; this presumably leads to somewhat higher energy requirements. Several of these process steps occur in the countries where the bauxite is mined (e.g., Australia, Jamaica, Surinam, Brazil, Venezuela), so the energy use and emissions also occur there.

Ceramic production may add significant additional energy due to the high temperatures required. To produce the electrolyte, bauxite is reacted with sodium salts and sintered at 1600°C for 5 min to get the correct structure. [18] After the reaction step, the electrolyte powder is pressed into tubes; there is some release of organic additives during the final heating step. The heating may be accomplished by electrical resistance, but RF induction has also been used, and microwave heating is possible. Energy requirements for electrode fabrication range from 9.3 to 30×10^6 Btu per 25-kWh battery assembly. [Based on 19] The lower end of the range generally applies for continuous production, but wide variations are associated with production route and equipment.

No recycling process for the electrolyte material has been postulated, nor is information available on process emissions or possible production plant locations.

Steel- Total energy for production of parts from virgin steel sheet is about 56.1×10^6 Btu/t; for recycled production, it is about 44.8×10^6 Btu/t. Over half of the energy used in production of virgin steel sheet products comes from the coal used to produce coke for the blast furnace.

Particulate emissions from raw-material handling at sinter plants, including iron oxides, sulfur oxides, carbonaceous compounds, and chlorides, can be controlled with hoods and a baghouse. Particulates, mainly iron oxides, are also generated during casting at the blast furnace, during oxygen blows in the basic oxygen steelmaking process, in electric-arc melting, and in casting operations, and they can be captured in hoods or other systems and sent to a baghouse, or for some operations, suppressed. Uncontrolled particulate emissions are on the order of 70 kg/tonne (140 lb/t) of steel. Control efficiencies range from 91 to 99%. Primary iron and steel production in the U.S. is concentrated in a band from Pennsylvania across to Illinois, near several major population centers. Secondary production is more widely distributed, with mini-mills in all parts of the U.S.

RECYCLING PATHS- The most common failure mechanism for Na-S batteries is failure of the solid electrolyte, which is subject to fracture. This may result in electrical failure and even fire. Corrosive sodium sulfides may attack the chromium-plated container housing the positive sulfur electrode, yielding chromium polysulfides. These build up around the beta-alumina and block the flow of sodium ions. [10] Therefore, the electrolyte would need to be replaced, as well as the positive electrode housing. The electrode materials would at least require purification and makeup of reacted materials during recycling. The massive battery case could possibly be reused.

Recycling is not economical yet, so batteries completing their useful lives now are incinerated, but other processes have been developed. Additional details and variants can be found in a German patent filed in 1993 by Silent Power. [20] The external enclosure is removed, and the strip of cells shredded. The ceramics, graphite, and metal are separated. The reactants are dissolved in a water-filled vessel, and sulfuric acid added. Because the temperature is kept in the relatively low range of 80 to 130°C, energy consumption for the process is low. The products are hydrogen gas, hydrogen sulfide (which is treated with a small-scale Claus process to get elemental sulfur product), and sodium sulfate (also treated for sale). The stainless steel outer container can be recycled, as can the steel or aluminum cell cases. The ceramic electrolyte could perhaps be used as a filler for concrete. The sulfur has been successfully reused in new batteries in laboratory trials. There are appropriate emissions controls on the processes, and the cost is projected to be $6-10/kWh to recycle, compared to the current $40-60. The process is claimed to have no gaseous emissions.

An alternative method to recycle some designs of Na-S batteries is to cool them to 100°C, pour out the sodium through a hole in the chamber, and shred the rest. The sulfur can be recovered, and the sodium is purer than virgin material because of filtration through the electrolyte. [21]

NREL reports that a spent 25-kWh battery would contain 50 kg sodium polysulfides (hazardous) and cites sodium sulfide as a potentially salable product. [13] There are possible environmental objections to recycling of Al, steel, and Cu from batteries.

NICKEL-CADMIUM BATTERIES

Large nickel-cadmium batteries are commercial for industrial uses. Although automotive battery design is likely to differ somewhat from industrial designs, some insights can be obtained. Several EV types are expected to use Ni-Cd batteries, including the Mazda Miata, the Nissan FEV 2-seater, the Griffon van (SAFT battery), and the Peugeot 106 and Citroen AX, hybrids with diesel power generators, and many others. The Chrysler TEVan (Caravan) has been tested with Ni-Cd batteries.

A battery with a life of 2000 cycles would last 6 to 10 years, and therefore might not need replacement over the vehicle's lifetime. [22]

BATTERY DESIGN- The Ni-Cd battery can operate from -40°C to 80°C. There are few design details in the literature. The active material in the sintered positive electrode is $Ni(OH)_2$, but the overall composition is ferronickel, with nickel, iron, and sometimes graphite constituents. The negative electrode is cadmium and iron, compact and plastic-bonded. Another design features "fiber-structured" electrodes. Potassium hydroxide (KOH) is used as the electrolyte, and there are thin layers of separators in the array. The cases generally aremade from nickel-plated steel sheet, with sheet steel lids and bases; PP cases are also possible.

BATTERY MATERIALS- The energy density is not much higher than that of the advanced lead-acid battery. At 57 Wh/kg, a 25-kWh Ni-Cd battery would weigh 439 kg (965 lb). New Ni-Cd batteries are reported to have an energy density of 60-65 Wh/kg, which would reduce the weight to as low as 385 kg (846 lb). [22] The electrodes are nonreactive. The positive plates [$Ni(OH)_2$] typically may contain 22% Ni (8% minimum) if the nickel is on an iron or graphite substrate. Other designs use nickel foam as the substrate and therefore use more nickel. The positive electrodes must contain less than 1% Cd and could possibly be reused. Several sources provide inconsistent estimates of overall material composition. The average Cd content of the battery is 15%. [22]

Emissions from battery production and recycling are expected to be small, as can be seen in a recent report. [3] Emissions from virgin material production are likely to be more significant.

<u>Cadmium</u>- Cadmium (Cd) is a by-product of zinc (Zn) manufacture. The zinc is smelted from sulfide ores, leading to SO_2 emissions that are recovered and used to produce sulfuric acid. It is unclear how much, if any, of the emissions should be attributed to the cadmium. Typically, 3 kg of Cd are produced per tonne of Zn. Between 2 and 10% of the Cd is left in Zn mining and beneficiation processes. In the pyrometallurgical production process, Cd is volatilized during the Zn roasting step and collected as flue dust, which may be dissolved with sulfuric acid, precipitated using Zn, and remelted into ingots.

An early U.S. Bureau of Mines report estimated the energy of Cd production from Zn flue dust at 166×10^6 Btu/ton, and from filter cake at 154×10^6 Btu/ton. [23] It is not known how overall process energy was allocated to the by-product, which is lower-melting and therefore could be argued to require less energy to produce. Cadmium is produced in the U.S. in Colorado, Illinois, Oklahoma, and Tennessee.

Cadmium is relatively easy to separate from other materials and recycle, because it melts at a low temperature and volatilizes into a gas, so recycling of cadmium is not expected to be energy-intensive. Cadmium is also chemically active and can be recovered by hydrometallurgical techniques.

<u>Nickel</u>- Although nickel is produced in the U.S., metal of sufficient purity is only produced at two sites, both outside of the U.S. The nickel used in electrodes for Ni-Cd and Ni-MH batteries is an extremely pure (>99.%) powder form (INCO 123) only produced by one company in the world, at plants in Wales and Canada. A similar material is reportedly being produced in Siberia. It is produced by the carbonyl process, in which carbon monoxide (CO) is reacted with nickel at 49°C to form nickel carbonyl ($Ni(CO)_4$). The cobalt, copper, and iron impurities are left behind. The nickel carbonyl is decomposed back to nickel at 232°C. Nickel carbonyl is toxic, so careful process control is necessary to avoid health and environmental hazards. Nickel recovered from spent batteries could probably be recycled to battery-grade material by using this process as well. Energy requirements for the carbonyl process are not currently available; a rough estimate for energy required to make virgin nickel from sulfide ores is about 105 million Btu/ton. [24] Smelting of such sulfide ores produces large quantities of SO_2. The U.S. Bureau of Mines estimates production of 8 tons of sulfur for each ton of nickel. [25] Expensive control equipment reduces emissions to much lower levels (1994 levels at one plant have been reduced 93% from 1978 levels), as mandated by the Clean Air Act Amendments in the U.S. and by other laws abroad. The SO_2 emissions from primary nickel for electrodes occur where the material is smelted overseas. In Canada, Inco has attained compliance with emissions regulations at great expense.

Potassium Hydroxide Electrolyte- An earlier study estimated an energy requirement of 9.3×10^6 Btu/ton for KOH. [26] Thus, this material's contribution to the total energy embodied in the battery will be small. The same type of electrolytic process is used to produce potassium as is used for sodium; therefore, the same concern about Hg emissions exists. If potassium is reacted with water to produce the hydroxide, care must be taken to avoid hydrogen emissions.

RECYCLING PATHS- Considerable information is available on recycling Ni-Cd batteries because facilities already exist; large Ni-Cd batteries are recycled in Japan, Sweden, and France. The technology for recycling is fairly straightforward because cadmium is low-melting and volatile and can be distilled off at relatively low temperatures for recovery. Because cadmium is toxic, careful control is required and facilities would need treatment and disposal permits. Nickel, now classified as a hazardous air pollutant, faces tight regulation as well.

One process, which could be used for large or small batteries, is reported to pyrolyze the organics; distill, refine, cast, and mold the Cd; and smelt the remaining ferronickel.

In an industrial Ni-Cd battery recycling process that operated in North Carolina, the batteries were discharged and the electrolyte removed, purified, and reused; the alkaline electrolyte could be used to recover metals from plating solutions. The remainder of the battery was shipped to Sweden. There, recycled batteries are dismantled and the electrodes separated. The positive electrode is sold to steelworks for input to stainless steel manufacture. The negative electrode is rinsed and placed in a topping furnace, where the Cd is distilled at 900°C for use in new electrodes. The steel containers are washed and sold to steelworks; plastic jars are cleaned, ground, and reused in new products, like pipe protectors. Although the Ni-Cd battery is durable and its hardware components are subject to only limited corrosion, the nickel electrodes would require reduction before reuse. This would be desirable if the market for alloying elements became saturated. One reported failure mechanism is the buildup of carbonates in the electrolyte; in that case, partial replacement of the electrolyte (50-70% can be easily removed) could extend the battery's useful life. [10]

In the U.S., Ni-Cd batteries are being recycled by INMETCO, which uses a pyrometallurgical process to produce ingots of alloying elements for use in stainless steel manufacture. A rough calculation suggests that the nickel from EV batteries could saturate this market. In addition, the pure metal is a more valuable product (it is not economical to separate it from small batteries); the obvious solution is to consider closed-loop recycling processes that return the nickel to batteries. The carbonyl process would produce electrode-quality nickel. Another alternative might be to melt the nickel under vacuum and produce a powder product with a spray. In the INMETCO process, the Cd is fumed off and collected. INMETCO used to sell the material to a zinc smelter, but they have since built their own Cd recovery unit. No information on emissions is available.

NICKEL-METAL HYDRIDE BATTERIES

Small nickel-metal hydride batteries have been in commercial use in electronic equipment like computers and telephones since 1987. Vehicle batteries are expected to be ready for production in 1996 by GM Ovonic (Troy, Mich.); Hyundai will use the Ovonic battery in its EV. Other manufacturers are also developing Ni-MH batteries. Ovonic claims that its battery's life would be similar to that of the vehicle, so the battery would not need to be replaced. [27] Other estimates suggest that the battery would only last 3-5 years. [22]

BATTERY DESIGN- This type of battery does not operate at high temperatures, but it does need some cooling because it is sealed and pressurized. The positive electrode is composed of nickel hydroxide, $Ni(OH)_2$. The negative electrode is one of several specially-engineered metal hydrides, multiple-alloy metal matrix composites that use rare earths or vanadium, nickel, titanium, zirconium, chromium, and manganese. These composites are amorphous, meaning that the atoms are in disarray rather than being aligned. The electrolyte is 30% aqueous potassium hydroxide, referred to as "starved" because there is no free electrolyte. Rather, it is all entrained in porous electrodes or PP separators. Therefore, the battery may be classed as "dry" for regulatory purposes. The individual cells are sealed prismatic containers, typically made of stainless steel. Several different designs are available, differing primarily in the hydride composition; that used by Ovonic is designated as the AB_2 type and that by SAFT, the AB_5.

In the Ovonic design, the electrodes are thin flat plates, separated by insertion in porous PP bag separators, which are stacked in multilayer sandwiches. A stack of electrodes forms a battery cell (~10 x 18 x 2.5 cm), weighing 1600 grams. Each cell has two terminals coming out of the top, on small nylon disk spacers. The case is 4-mil-thick stainless, with a plastic shrink-wrapped cover. The cells are assembled into six 12-volt modules, which are secured in battery-pack trays (made of ABS plastic or aluminum) designed by the auto manufacturer.

BATTERY MATERIALS- A high energy density of about 70-80 Wh/kg is expected to result in a relatively compact, lightweight battery. A 25-kWh battery would weigh about 330 kg (730 lb). Current technology could raise the energy density to over 120 Wh/kg, and the developer has speculated that advanced materials and configurations have the potential to achieve up to 500 Wh/kg. [28] Such a major breakthrough could lower the weight of an EV battery pack to about 100 lb.

Published estimates of materials in Ni-MH batteries differ in the quantities of KOH electrolyte, the composition of the hydride electrode (whether or not iron is the substrate for the hydride electrode), and the amount of steel in the case. This is not surprising, since different designs are being considered at this stage.

Nickel- The nickel electrodes in Ni-MH batteries are essentially the same as those in Ni-Cd batteries. The Ovonic positive electrode uses thin flat plates of nickel foam, with $Ni(OH)_2$ on the surface.

Metal Hydride Electrode- The various Ni-MH battery designs differ mainly in the composition of the metal hydride negative electrode. The AB_5 type uses a rare-earth Misch metal (typically $LaNi_5$, with naturally occurring rare-earth combinations that can include Ce, Nd, and Pr) and the AB_2, a vanadium-rich refractory alloy. Relative elemental weights for an AB_2 negative electrode might be 22.7-40.9% V, 20.5-35.9% Ni, 20.2-25.4% Zr, 8.4-16% Ti, and 0-1% Mn. The negative electrode powder from scrap AB_5 consumer cells was found to contain typically 33% rare earths, 60% transition metals, and 7% other metals (Mn, Al) by weight. [29]

The flat plate hydride electrode of the Ovonic battery consists of the amorphous or polycrystalline hydride powder pressed onto a woven nickel grid that serves as its base. The alloy is produced by vacuum induction melting, which is relatively energy-intensive because of the high temperatures required to melt V and Zr. The alloy is very hard and is only partially broken before hydriding. After the hydride is produced, the material can be ground more easily to a powder for pressing onto the electrode.

RECYCLING PATHS- No facilities are yet available for recycling Ni-MH batteries, except for INMETCO's, which can produce pigs for alloying stainless steel. In this process, INMETCO can recover the Ni, Fe, Cr, and Mn, and part of the Va, as alloying elements; the rest of the elements go to the process slag for sale as aggregate. [30] Because (1) this process does not recover valuable elements like Ti and (2) the stainless steel market may be too small to accommodate the materials from large numbers of EV batteries, closed-loop recycling or recovery of more valuable separated materials might be preferable. Since Ni-MH batteries embrace many different technologies and combinations of elements, a generic discussion of recycling processes is of limited value; design-specific analyses will eventually be necessary.

A recent study by NREL estimated costs, including energy costs, for potential recycling processes for Ni-MH automotive batteries. [31] Direct energy use for the different processes was in the range of 4-14 x 10^6 Btu/ton of batteries processed, almost all in the form of electricity. However, these estimates only include the process steps at the recovery facility, not those at other facilities required to produce products from the separated scrap. In addition, the energy embodied in the material inputs to the processes is not included.

Recycling processes can begin by dismantling of the battery or by chopping of the entire structure, followed in either case by washing to remove and neutralize the electrolyte. In general, we expect dismantling to be preferable for large automotive batteries because it enables the separation and recovery of purer materials. In the case of the Ni-MH batteries, it is advantageous to remove the electrodes from the case so that Ni can be recovered with little or no Fe content.

Dismantling, followed by separate recovery of the electrodes, is possible. However, the spent electrodes may not be structurally sound (due to corrosion and oxide formation), and the surface powders may have migrated to some degree. [32] [33] Recycling back to battery materials, technically feasible for the nickel electrodes, may be more difficult for the metal hydride electrodes because the spent metal hydride electrodes are believed to be highly oxidized. Reprocessing, if possible, would be energy-intensive and should be compared with primary production. Currently, MH electrode manufacturing scrap is recycled back to electrodes, but no information is available on post-consumer electrodes. The grain structure is determined during cooling, so there is no reason to believe that recycled material with the appropriate properties could not be fabricated.

Separation of the metals from mixed scrap and recovery as high-value materials is difficult. However, the melting and boiling points differ, so pyrometallurgical separation may be possible, but some of the valuable elements may be lost to the slag. Hydrometallurgical processes are being developed by the U.S. Bureau of Mines. For either battery type, the basic technique would be to leach the internal components in a mineral acid and recover the metals by techniques like solvent extraction and precipitation or electrowinning. These processes hold promise for recovering the Ti, V, and Zi from AB_2 scrap, as well as the Ni and Cr, as valuable salts. Phosphate salts of La and Ce could be recovered from AB_5 scrap and processed with the phosphate concentrate from ore processing. [29] The PP separator material would float, making it easily recoverable.

So far, only the KOH electrolyte has been classified as a hazardous waste.

ENERGY USE FOR PRODUCTION AND RECYCLING

Rough estimates of energy required to produce and recycle a 25-kWh battery of each of the four selected types are shown in Tables 2-5. These estimates are not complete, because technologies for recycling all of the materials have not yet been developed. In addition, material composition data for several of the battery types were poor, and production information was not readily available. Several rough approximations were made in order to identify important contributions to energy use for material production. Materials present in very small quantities or having very low production energies were generally assumed not to be recycled. In spite of the uncertainties, however, it is possible to make some interesting observations.

As expected, the most complete data were available for advanced lead-acid batteries. If the battery were made from all virgin materials, 76% of the energy to produce it would go for lead production, with most of the rest for production of the PP case. The energy to produce the battery from virgin materials for a mini-compact car in the 2003-2007 time period (one of the EVTECA characterization periods) is approximately 17% of the energy required to produce the rest of the car. However, production from recycled materials reduces the energy required by more than a factor of four, and battery lead and cases are already recycled to a very large extent. Energy to produce an 80%-recycled battery pack for a mini-compact would then represent under 7% of the vehicle's production energy. Requiring a replacement battery would, of course, double that energy contribution, but even if replacement were needed, this might be the least energy-intensive battery to produce. This does not take into account extra vehicle mass required to support a heavier battery, or extra energy to carry it around for the vehicle's lifetime.

Although data were very scarce for the sodium-sulfur battery, several conclusions are possible. The quantities of active material in this battery are relatively small, and sulfur production uses little energy. Therefore, energy use in producing this type of battery would be dominated by that for production of the steel cell cases and thermal enclosure. Recycling of these items would not mean major energy savings, because the energy-intensive fabrication steps would be required again. However, reuse would save essentially all of the production energy. The cell cases would probably not be reusable because of corrosion and because dismantling might not leave them intact, but the thermal enclosure could probably be reused. The energy density of this battery type is the highest of those included in this study. Therefore, less battery weight is required per pound of vehicle, and the relative contribution of battery production to total vehicle production energy is reduced. In addition, no battery replacement is expected over the vehicle lifetime.

The nickel-cadmium battery, which uses significant quantities of energy-intensive material inputs, has a rather high energy requirement (about four times that of the Pb-acid battery). Over 80% of the energy input is used for production of electrode materials. However, this is based on assignment to cadmium of the same energy intensity as zinc, which may not be appropriate. The next largest contribution is from the stainless steel battery case, although this is replaced by lighter plastics in some designs. In addition, because this type of battery has a relatively low energy density, the mass of battery material per unit vehicle mass is high. Therefore, it is important from an energy standpoint to recycle the electrode materials. It should be possible to recycle the nickel, but no estimate of recycling energy is available. Cadmium recycling is currently feasible and not very energy-intensive; cadmium volatilizes at relatively low temperatures. Cd recycling alone could save over one-third of the battery production energy. For a compact car in the 2003-2007 time period, the Ni-Cd battery would require over 90% as much energy to produce as would the remainder of the vehicle. Therefore, recycling of this battery type is essential on energy grounds; potential health hazards from Cd release are another powerful incentive to keep the material within a closed cycle.

Data for nickel-metal hydride battery materials are difficult to obtain, but some conclusions are possible. The nickel electrode is very similar to that in the Ni-Cd battery, meaning it is energy-intensive but recyclable. Recycling of the metal hydrides is still at the research stage, but progress is being made. The separator material is recyclable, and this improves the overall energy picture. While this type of battery is relatively energy-intensive (approximately 75% as energy-intensive as the Ni-Cd on an equal-mass basis), the energy density is considerably higher than that of the Ni-Cd. Therefore, the overall contribution of the Ni-MH battery production energy to total vehicle energy would be only about 60% that of the Ni-Cd. For the 2003-2007 compact car, the battery production energy is about 45% of that for the rest of the vehicle. If the case were lighter, less energy would be used. Recycling of the electrode materials could also reduce energy requirements.

This preliminary analysis allows us to focus additional effort on data collection for those materials that make significant contributions to the energy required for battery production and for which older or approximate data were used. Examples are the electrode materials for the Ni-Cd and Ni-MH batteries. The analysis also points to these materials as important targets for recycling research to reduce the energy required to supply the batteries. In addition, it identifies places where recycling will not significantly reduce energy use; in such cases, reuse or possibly substitution of a lighter design or a less energy-intensive material is suggested. An example of that is the stainless steel in sodium-sulfur batteries, where the thermal enclosure can probably be reused.

Finally, energy use for battery production must be put into the perspective of the car's entire lifecycle. An electric vehicle that used 0.25 kWh/mile would, over a lifetime of 100,000 miles, use electricity that required 260 million Btu to generate (assuming 10,500 Btu/kWh). A similar, small conventional vehicle, getting 35 mpg on reformulated gasoline, would consume about 320 million Btu of fuel. Thus, even if the most energy-intensive battery design were used and not recycled, energy use for battery production would be less than 20% (42.8/260 — see Table 4) of the vehicle's lifetime fuel consumption.

Table 2- Advanced Lead-Acid Battery Material Energy

Material	Weight-Percent	Production Energy (10^6 Btu/ton)	Recycle Energy (10^6 Btu/ton)	Energy per 25 kWh (10^6 Btu)	
				Virgin Batteries	Recycled Batteries
Lead	69	23.4	4.6	8.9	1.8
Electrolyte	22				
Sulfuric Acid (pure)	7.9	0.5 (est.)	N.A.	0.02	0.02
Water	14.1	0.03	N.A.	0.00	0.00
Case and Cover (polypropylene)	6.1	68	13	2.3	0.44
Separators (glass mat)	2.1	22.3	18.9	0.25	0.22
Other	0.8	30 (est.)	N.A.	0.13	0.13
TOTAL	100			11.7	2.5

Table 3- Sodium-Sulfur Battery Material Energy

Material	Weight-Percent	Production Energy (10^6 Btu/ton)	Energy per 25 kWh, Virgin Batteries (10^6 Btu)
Sulfur	12	0.8-8	0.03-0.26
Graphite			
Sodium	8	92	2.0
Ceramics	20	20	1.1
Steel	<60	66	<10.9
Fiberglass		22.3	
Other		30 (est.)	
TOTAL			~14.2

EMISSIONS IN PERSPECTIVE

Even though the fuel mix for material production is somewhat different than the utility mix, emissions from fuel combustion during battery production are much less important than those from electricity generation. The major environmental advantage of EVs is touted to be their air pollution benefits. Utility emissions replace conventional gasoline vehicle (CV) emissions. The utility emissions can be lower than those of CVs in terms of either grand totals or population exposure (because the power plants operate outside major population centers). Therefore, it seems reasonable to provide a brief assessment of the utility emissions associated with EVs.

For the EVTECA, we analyze the effect on power-plant emissions of the use of EVs in four metropolitan areas. The areas vary by utility fuel mix, as well as other variables (e.g., climate). Both low and high EV market-penetration scenarios are evaluated. The utility analysis examines several charging scenarios: unconstrained charging of EVs when they return "home" and peak-shift charging of EVs, in which the utilities use various measures to postpone the initiation of EV charging. In each of the charging scenarios, capacity is added where required to maintain system reliability. The additional capacity is assumed to be either combined cycle (CC) or combustion turbine (CT) units. Economic dispatch is employed, except that in Chicago, control of SO_x emissions necessitates environmental

Table 4- Nickel-Cadmium Battery Material Energy (FNC type)

Material	Weight-Percent	Production Energy (10^6 Btu/ton)	Energy per 25 kWh, Virgin Batteries (10^6 Btu)
Nickel	20.2	105	10.2
Nickel Hydroxide	17.4	66[1]	5.5
Cadmium[2]	24.6	166	19.7
Cobalt	1.4	80 (est.)	0.6
Steel and Copper Terminals[3]	4.1	93	1.8
Electrolyte	17.4		
KOH (pure)	5.22	9.3	0.23
LiOH (pure)	0.70	10 (est.)	0.04
Water	11.48	0.03	0.00
Case and Cover (stainless)	11.7	66	3.8
Miscellaneous Plastics	3.1	68	1.02
Other	0.1	30 (est)	0.02
TOTAL	100		42.8

[1] Assumed produced from pure nickel
[2] 88% Cd, 12% CdO
[3] Assumed 50% Cu, 50% steel for estimation purposes

dispatch to control these emissions. Estimates have been developed for each season of the year. The analysis estimates both marginal and average emissions rates associated with use of EVs.

The EVTECA contains a wealth of estimates of utility emissions from the use of EVs. Table 6 contains an example of the results: total EV emissions in Chicago under the high EV scenario, assuming unconstrained charging and environmental dispatch, and presenting only the marginal emission results. Additional capacity of 471 MW beyond that already planned is required under this scenario. EV emissions when the addition of CT and CC units is assumed are shown.

Although use of EVs might be expected always to lead to increases in air pollutants over a base with no EVs, the effect of adding CC capacity because of EV demand is to reduce the selected emissions associated with EVs relative to the base utility emissions, as indicated in Table 6. This result deserves some explanation. In the utility analysis, when capacity is added, the power plant is not sized to provide only for the additional capacity required by EVs. Furthermore, the CC units added are cheaper and cleaner than some existing units. As a result, the new CC units displace "dirtier" and more expensive units in the dispatch order and the total emissions associated with total generation decrease relative to the base. Thus, the marginal emissions are negative.

For purposes of this paper, the total EV emissions results for the Chicago high scenario have been translated into an estimate of the average utility emissions associated with the average EV over its life. We know that the utility emissions will vary in different years, and thus the number presented is not exact, but it does provide some perspective on the emissions associated with battery production and recycling. Average emissions per vehicle are presented in Table 6 (pounds throughout vehicle life, assumed to be 100,000 miles).

Finally, Table 6 also presents the relationship of EV emissions to those of CVs for this scenario. The CVs operate on reformulated gasoline (RFG). Emissions associated with the production of RFG are not included. Use of EVs leads to significant VOC and CO reductions. NO_x and SO_2 may increase or decrease, depending on which type of unit provides the new capacity for EV charging. Use of EVs leads to increases in TSP and CO_2 emissions. Again, these results are just a sample of the results available from the EVTECA.

Table 5- AB_2 Nickel-Metal Hydride Battery Material Energy

Material	Weight-Percent	Production Energy (10^6 Btu/ton)	Energy per 1000 lb, Virgin Batteries (10^6 Btu)
Nickel	16.4	105	6.3
Nickel Hydroxide	12.1	66	2.9
Metal Hydride (V, Zi,Ti, Cr, Al)	12.9	100 (est.)	4.7
Separators (polypropylene)	5.0	68	1.2
Electrolyte	9.0		
KOH (pure)	3.0	9.3	0.10
Water	6.0	0.03	0.00
Iron	14.5	38	2.0
Stainless Steel	29	66	7.0
Other	1.1	30 (est.)	0.12
TOTAL	100		24.5

Table 6- EV Utility Emissions in the Chicago High EV Scenario in 2010, Assuming Unconstrained Charging and Environmental Dispatch (Marginal Emissions Results)

	Combustion Turbine Provides New Capacity			Combined Cycle Provides New Capacity		
Emissions	Annual Total (tons)	Pounds throughout Vehicle Life	Relative to CVs	Annual Total (tons)	Pounds throughout Vehicle Life	Relative to CVs
VOC	46	4	0.03	12	1	0.01
NO_x	2,870	258	1.78	(4,529)	(408)	-2.81
CO	499	45	0.03	(581)	(52)	-0.03
SO_2	684	62	7.20	(164)	(15)	-1.73
TSP	412	37	9.35	688	62	15.61
CO_2	1,196,254	107,683	1.47	1,174,614	105,735	1.44

CONCLUSIONS

In summary, there may be significant energy and environmental consequences to production and recycling of electric vehicle batteries. All of the details of the processes must be given careful attention during battery design and construction to minimize possible impacts. However, there appear to be no "show-stoppers": There are no potentially devastating impacts or major technical or institutional barriers caused by production and recycling of battery materials that would prevent the introduction of electric vehicles on a large scale.

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