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by

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Impacts of EV Battery Production and Recycling

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Abstract. Electric vehicle batteries use energy and produce environmental residuals when they are produced and recycled. This study estimates, for four selected battery types (sodium-sulfur, nickel-metal hydride, nickel-cadmium, and advanced lead-acid), 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. Nickel-cadmium and nickel-metal hydride batteries are similar, for example, but energy requirements for the production of cadmium electrodes may be higher than those for metal hydride electrodes, while 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 compare it with one for conventional vehicles. This comparison will help DOE to evaluate EV technology and address any potential environmental problems. Work is being carried out at Argonne National Laboratory, Pacific Northwest National Laboratory, and the National Renewable Energy Laboratory. The work described here is part of the EVTECA study. A more detailed version of this paper is available (1).

Much has been written about the performance of batteries for EVs, but information about the materials and their production and recycling processes is not readily available. Such processes have 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 EV batteries: advanced lead-acid (Pb-acid), sodium-sulfur (Na-S), nickel-cadmium (Ni-Cd), and nickel-metal hydride (Ni-MH).

Some insights about battery materials apply to all four types, to varying degrees. The batteries will make up a significant fraction of vehicle mass (~20-40%). The impacts are magnified because some of the batteries will have shorter lifetimes than the vehicles and must be replaced. Some thought is going to battery recyclability at the design stage, because the EV is being "born green." In contrast to small consumer cells (now simply chopped up), EV batteries will be large enough to warrant disassembly and material segregation (manual or automated) as the first step in recycling. Work on methods for reclaiming some materials is, at best, incomplete.

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

Production of battery materials generates emissions from physical and chemical processes and from combustion of fuels to drive these processes. Process emissions differ with material, but fuel combustion emissions are standard combustion products, which we compare with those produced by operating the car over its lifetime.

ENERGY USE FOR PRODUCTION AND RECYCLING

Table 1 lists several key characteristics for the four selected types, including rough production and recycling energy estimates for a 25-kWh battery (reasonable size for a small car). The data are incomplete because technologies for recycling all of the materials have not yet been developed. Where material composition and production data for several battery types were not readily available, we made rough approximations 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 assumed not to be recycled. In spite of these shortcomings, we can make some interesting observations.

The most complete data were available for advanced Pb-acid batteries. If the battery were made from all virgin materials, 76% of the energy would go to Pb production and most of the rest to the polypropylene case. The energy to produce the battery for a mini-compact car from virgin materials is approximately 17% of that required to produce the rest of the car. However, production from recycled materials reduces the required energy by more than a factor of four, and battery Pb and cases are already recycled to a great extent. Energy to produce an 80% recycled battery pack would then represent less than 7% of the vehicle's production energy. Requiring

TABLE 1. Battery Comparison

Item	Pb-Acid	Na-S	Ni-Cd	Ni-MH
Electrode Materials	Lead-on Fiberglass Mesh	Molten Sodium and Sulfur	Nickel Hydroxide and Cadmium/iron	Nickel Hydroxide and Metal Hydride
Electrolyte	Sulfuric Acid	Beta Alumina Ceramic	Potassium Hydroxide	Potassium Hydroxide
E Density (Wh/kg)	50	100	57	75
Mass for 25 kWh (kg)	500	250	439	330
E to Make (Recycle) (10 ⁶ Btu)	11.7 (2.5)	~25.8 ^a	~42.8	24.5
Significant Emissions	Lead Particulates	Iron Oxide Particulates	Cd Fumes (?)	Unknown
Comments	Short Battery Life, Existing Recycling Infrastructure	Operates at 350°C	Cd Energy Allocated by Mass, Low Recycle E	MH Recycling Process Unknown

^aThis total reflects a revised estimate for ceramic electrolyte production, based on Ref. 2.

one or more replacement batteries would multiply that contribution, but even if replacements 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 transport it over the vehicle's lifetime.

Although few data were available for the Na-S battery, several conclusions are possible. The quantities of electrode material in this battery are relatively small, and sulfur production uses little energy. The energy used in producing this type of battery will be dominated by that for production of the ceramic electrolyte, steel cell cases, and thermal enclosure. Recycling these items would offer some energy savings, but reuse would save essentially all of the production energy. No method has been identified for recycling the electrolyte, which would not be reusable. The cell cases would probably not be reusable, because of corrosion and because dismantling might not leave them intact, but recycling is possible. 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.

Because the Ni-Cd battery uses energy-intensive material inputs, it has a high energy requirement (about four times that of the advanced Pb-acid battery). More than 80% of the energy is used to produce the electrode materials. But this is based on assigning the energy intensity of Zn to Cd, a Zn by-product, which may be inappropriate. The next-largest contribution is from the stainless steel battery case, replaced by lighter plastics in some designs. Because this type of battery has a relatively low energy density, the mass of battery material per unit vehicle mass is high, so it is important, from an energy standpoint, to recycle the materials. Nickel recycling is possible, but no energy estimate is available. Cadmium recycling is currently feasible and not very energy-intensive, because Cd volatilizes at relatively low temperatures. Recycling of Cd alone could save over one-third of the battery production energy. The Ni-Cd battery would require more than 90% as much energy to produce as would the remainder of a compact vehicle; therefore, recycling is essential on energy grounds. Potential health hazards from Cd release are another powerful driver to maintain a closed cycle.

Data for Ni-MH battery materials are hard to obtain, but some conclusions are possible. The Ni electrode is 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; little can be said except that progress is being made. The plastic 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 Ni-MH battery production energy to total vehicle energy is only about 60% that of the Ni-Cd. For a compact car, Ni-MH battery production energy is about 45% of that for the rest of the vehicle. A lighter case would use less energy. Recycling of the electrode materials could also reduce energy requirements.

This preliminary analysis allows us to focus additional effort on collecting data on those materials that contribute significantly to battery production energy requirements and for which older or approximate data were used. Examples include electrode materials for 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 and identifies those batteries for which replacement would mean a large energy penalty. It also identifies places where recycling will not significantly reduce energy use, so reuse or perhaps substitution of a lighter design or a less energy-intensive material is indicated.

Finally, energy use for battery production must be put into the perspective of the car's entire life cycle. Over a lifetime of 100,000 mi, a 0.25-kWh/mi EV would use electricity that required 260 million Btu to generate (assuming 10,500 Btu/kWh). A similar, small conventional vehicle (CV) 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, production energy use would be less than 15% of the vehicle's lifetime fuel consumption.

PROCESS EMISSIONS

As with many other metals, primary Pb is produced from sulfide ores by sintering, blast-furnace reduction, and refining. The primary effluent, SO₂, is recovered and used to produce sulfuric acid. Missouri accounts for 75% of primary Pb production in the United States. Cadmium, produced in Colorado, Illinois, Oklahoma, and Tennessee, is smelted from zinc sulfide ores. It is unclear how much of the emissions should be attributed to Cd. Nickel is also smelted from a sulfide ore. The U.S. Bureau of Mines estimates 8 tons of sulfur produced for each ton of Ni (3). Note that SO₂ emissions from primary Ni for electrodes occur where the material is smelted, overseas. In Canada, Inco has attained compliance with emissions regulations, at great expense.

Lead compounds, such as oxides, are released as particulates during both primary and secondary (recycling) Pb smelting operations and during battery manufacture and recycling. Control systems are required in the United States. Secondary smelting and battery recycling, more geographically spread out than primary production, may occur near population centers. Currently, >90% of the Pb and oxides from batteries are recycled or exported. If scrap is exported to Asia, smelters operating with less stringent (or no) pollution-control regulations could have an economic advantage but cause severe local health effects.

About 63% of the elemental sulfur consumed domestically 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 has a positive impact on air quality, since the material would otherwise contribute to emissions.

Particulates, including iron oxides, sulfur oxides, carbonaceous compounds, and chlorides, are emitted at several stages of primary and secondary iron and steel production. These materials can be captured in hoods or other systems and sent to a baghouse or, in some operations, suppressed. Primary production is concentrated in a band from Pennsylvania to Illinois, near several major population centers. Secondary production is more widely distributed, with mini-mills around the country.

COMBUSTION EMISSIONS IN PERSPECTIVE

Although the fuel mix for material production differs from the utility mix, emissions from fuel combustion during battery production are much less important

than those from electricity generation. The most touted environmental advantage of EVs is supposed to be their air pollution benefit. Utility emissions replace CV gasoline emissions. The utility emissions can be lower in terms of grand totals than those of gasoline vehicles, or in terms of population exposure because the power plants operate outside major population centers. The effect on power plant emissions of the use of EVs in four metropolitan areas was analyzed. The areas varied by utility fuel mix as well as other variables (e.g., climate). Both low and high EV market penetration scenarios were evaluated. The utility analysis examined several different scenarios for charging, EV market penetration, and plant dispatch.

Use of EVs might be expected always to lead to increases in air pollutants from utilities over a base with no EVs, but the effect of adding capacity because of EV demand may in some cases reduce utility emissions relative to the no-EV base. This result deserves some explanation. In the utility analysis, when capacity is added, the power plant is the most economical size, rather than only providing for the additional capacity required by EVs. Added units are cheaper and cleaner than some existing units; as a result, new units may displace "dirtier" and more expensive units in the dispatch order, so total emissions decrease relative to the base. Thus, in some cases, marginal emissions are negative.

CONCLUSIONS

Production and recycling of EV batteries may have significant energy and environmental consequences. All process details must receive careful attention during battery design and construction to minimize possible impacts. However, there appear to be no "show-stoppers" — potentially devastating impacts or major technical or institutional barriers caused by production and recycling of battery materials — preventing the introduction of EVs on a large scale.

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