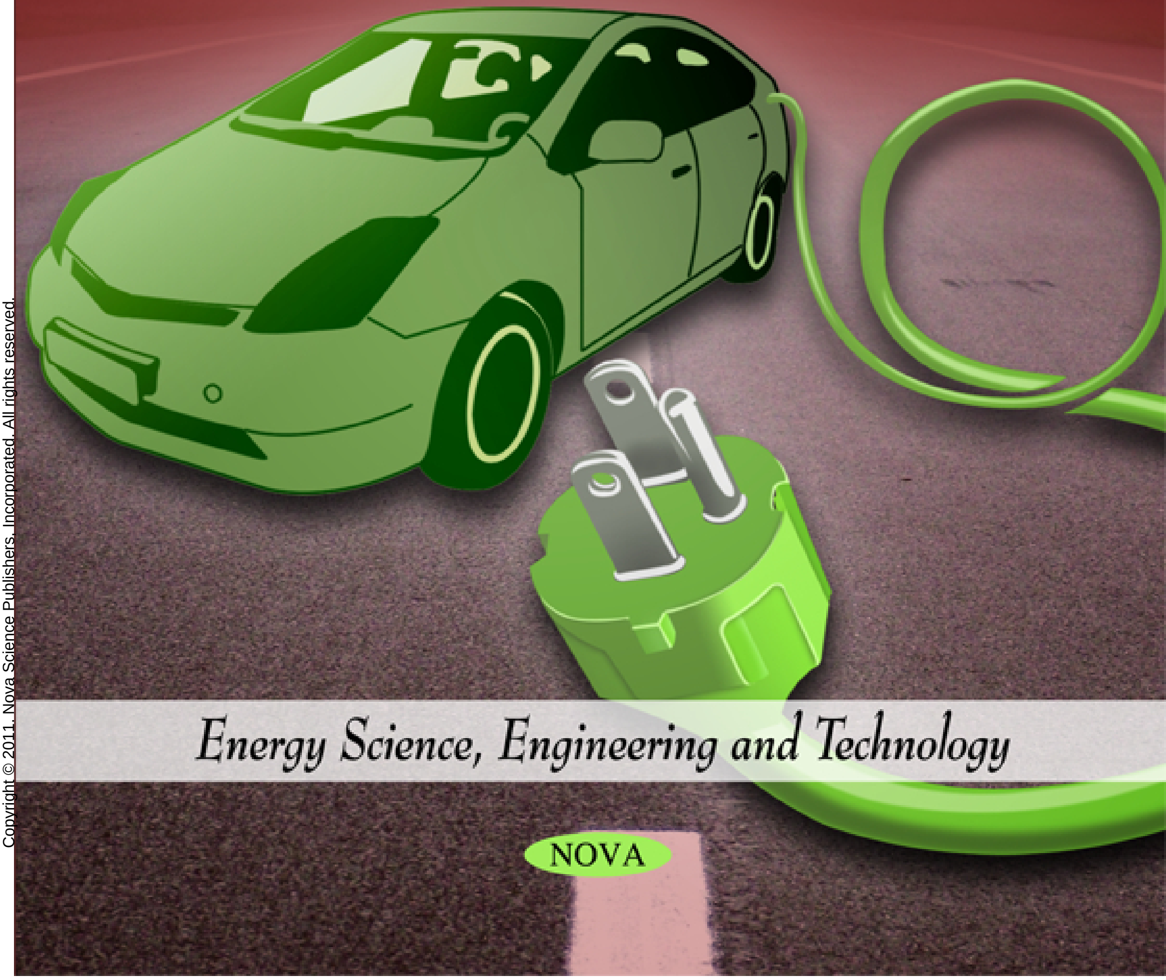
MALCOLM R. PERDONTIS
EDITOR

BATTERY MANUFACTURING AND ELECTRIC AND HYBRID VEHICLES



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PREFACE

The United States is one of several countries encouraging production and sales of fully electric and plug-in hybrid vehicles to reduce oil consumption, air pollution and greenhouse gas emissions. The American Recovery and Reinvestment Act of 2009 provided federal financial support to develop a domestic lithium-ion battery supply chain for electric vehicles. President Obama has called for 1 million fully electric vehicles to be on U.S. roads by 2015. In making a national commitment to building electric vehicles and most of their components in the United States, the federal government has invested $2.4 billion in electric battery production facilities and nearly $80 million a year for electric battery research and development. This book examines the nascent battery manufacturing industry and considers efforts to strengthen U.S. capacity to manufacture batteries and battery components for hybrid and electric vehicles.

Chapter 1- The United States is one of several countries encouraging production and sales of fully electric and plug-in hybrid electric vehicles to reduce oil consumption, air pollution, and greenhouse gas emissions. The American Recovery and Reinvestment Act of 2009 (ARRA, P.L. 111-5) provided federal financial support to develop a domestic lithium-ion battery supply chain for electric vehicles. President Obama has called for 1 million fully electric vehicles to be on U.S. roads by 2015.

Chapter 2- President Obama's goal of putting one million electric vehicles on the road by 2015 represents a key milestone toward dramatically reducing dependence on oil and ensuring that America leads in the growing electric vehicle manufacturing industry. Although the goal is ambitious, key steps already taken and further steps proposed indicate the goal is achievable.

Indeed, leading vehicle manufacturers already have plans for cumulative U.S. production capacity of more than 1.2 million electric vehicles by 2015, according to public announcements and news reports. While it appears that the goal is within reach in terms of production capacity, initial costs and lack of familiarity with the technology could be barriers. For that reason, President Obama has proposed steps to accelerate America's leadership in electric vehicle deployment, including improvements to existing consumer tax credits, programs to help cities prepare for growing demand for electric vehicles and strong support for research and development.

Chapter 3- We conducted a design study to compare the manufacturing costs at a level of 100,000 hybrid vehicle batteries per year for flexible package (Flex) cells and for rigid aluminum container (Rigid) cells. Initially, the Rigid cells were considered to have welded closures and to be deep-drawn containers of about the same shape as the Flex cells. As the study progressed, the method of fabricating and sealing the Rigid cells was expanded to include lower cost options including double seaming and other mechanically fastened closures with polymer sealants. Both types of batteries were designed with positive electrodes containing $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ and graphite negative electrodes. The use of a different combination of lithium-ion electrodes would have little effect on the difference in costs for the two types of cells. We found that 20-Ah cells could be designed with excellent performance and heat rejection capabilities for either type of cell. Many parts in the design of the Flex cells are identical or nearly identical to those of the Rigid Cell, so for these features there would be no difference in the cost of manufacturing the two types of batteries. We judged the performance, size and weight of the batteries to be sufficiently similar that the batteries would have the same value for their application.

Chapter 4- Concerns over the economic and energy security implications of the U.S. dependence on foreign oil, in addition to increasing apprehension about greenhouse gas (GHG) emissions and their impact on climate change, has spurred a renewed interest in improving the nation's energy efficiency. To address these concerns, a number of initiatives and policies have been established, including the Renewable Portfolio Standards enacted by many states to address the "greening" of their electricity grids. Another example involves recent actions by both the government and the auto industry to develop affordable, advanced battery technologies for vehicle traction. When used for partially and fully electrified vehicles, the advantages of such batteries would be reduced oil consumption and carbon dioxide (CO_2) emissions. In addition, when used for the grid, such batteries could supply a storage option for renewable energy generated during off-peak periods. However, the battery technologies required to provide traction in vehicles, with practical driving ranges between rechargings, represent a significant departure in material composition from the lead-acid (PbA) batteries found in conventional vehicles. Whether used for vehicles, the grid, or both, the question at hand is the level of environmental benefit that could potentially be provided by these batteries, considering their material differences and the sheer number that would be required.

Chapter 5- Several electrical energy storage and conversion devices have been considered for use in vehicle applications. These are illustrated in Figure 1 in the form of a Ragone plot, wherein the abscissa is specific power (which can be thought of as acceleration in a vehicle) and the ordinate is specific energy (or range in an EV). The graph shows these quantities for various batteries, electrochemical capacitors, and fuel cells. Note that this plot shows specific energy and power on a cell level for batteries made for many different applications, from consumer electronic to vehicles. An additional derating will need to be applied when analysis is done on the pack level. The figure shows that lithium-ion (Li-ion) batteries are superior to nickel metal hydride (Ni-MH) batteries for all three applications from a performance standpoint. The figure also shows that no battery system has the ability to provide energy close to what is possible with gasoline (Internal combustion, or IC-Engine). Finally, the figure suggests that batteries are superior to capacitors for applications where the time of discharge is greater than the order of seconds.

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Chapter 1

BATTERY MANUFACTURING FOR HYBRID AND ELECTRIC VEHICLES: POLICY ISSUES

Bill Canis

SUMMARY

The United States is one of several countries encouraging production and sales of fully electric and plug-in hybrid electric vehicles to reduce oil consumption, air pollution, and greenhouse gas emissions. The American Recovery and Reinvestment Act of 2009 (ARRA, P.L. 111-5) provided federal financial support to develop a domestic lithium-ion battery supply chain for electric vehicles. President Obama has called for 1 million fully electric vehicles to be on U.S. roads by 2015.

In making a national commitment to building electric vehicles and most of their components in the United States, the federal government has invested $2.4 billion in electric battery production facilities and nearly $80 million a year for electric battery research and development. To increase sales of such vehicles, the President has recommended that the current $7,500 tax credit for purchase of a plug-in hybrid be converted into a rebate, available immediately to car buyers upon purchase of a vehicle.

Developing appropriate batteries is the biggest challenge to increasing sales of electric and plug-in hybrid vehicles. Batteries for these vehicles differ substantially from traditional lead-acid batteries used in internal combustion

engine vehicles: they are larger, heavier, more expensive, and have safety considerations that mandate use of electronically controlled cooling systems. Various chemistries can be applied, with lithium-ion appearing the most feasible approach at the present time.

The lithium-ion battery supply chain, expanded by ARRA investments, includes companies that mine and refine lithium; produce components, chemicals, and electronics; and assemble these components into battery cells and then into battery packs. Auto manufacturers design their vehicles to work with specific batteries, and provide proprietary cooling and other technologies before placing batteries in vehicles. Most of these operations are highly automated and require great precision. It has been estimated that 70% of the value-added in making lithium-ion batteries is in making the cells, compared with only 15% in battery assembly and 10% in electrical and mechanical components.

Despite these supply chain investments, it may be difficult to achieve the goal of 1 million electric vehicles on U.S. roads by 2015. Costs remain high; although data are confidential, batteries alone are estimated to cost $8,000 to $18,000 per vehicle. Vehicle range limitations and charging issues may deter purchases. Lower gasoline prices and improvements in competing internal combustion engine technologies could slow acceptance of electric vehicles, whereas persistent high gasoline prices could favor it. Advanced battery manufacturing is still an infant industry whose technology and potential market remain highly uncertain. Its development in the United States is likely to depend heavily on foreign competition and how the federal government further addresses the challenges of building a battery supply chain and promoting advances in battery technologies.

INTRODUCTION

Since 1976, Congress has funded programs to develop high-density, low-cost batteries to operate electric and hybrid vehicles. In the American Recovery and Reinvestment Act of 2009 (ARRA, P.L. 111-5), Congress authorized support for lithium-ion battery manufacturing, with $2.4 billion in grants. In February 2011, President Obama asked Congress to further expand these initiatives with additional R&D funding requests and a recommendation that an electric vehicle tax credit be converted into a federally funded rebate program.

Promotion of electric vehicles and the batteries to power them is part of a long-standing federal effort to reduce oil consumption and air pollution. This effort has taken a variety of directions, including mandated use of biofuels and research into hydrogen-fueled vehicles. Development of vehicles that use electricity as a power source, either by itself or in conjunction with smaller, supplementary internal combustion engines, is part of this initiative. In general, the cost of operating a plug-in hybrid or all-electric vehicle will be substantially less than fueling a gasoline-powered car or truck, but up-front costs are likely to be much higher. Depending on the source of the electricity, the carbon footprint of an electric vehicle may be less than that of a vehicle with a traditional internal combustion engine.[1]

The major hurdle in providing a large national fleet of hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fully electric vehicles (EVs) is the size, cost, weight, durability, and safety of the batteries that would power them. Because battery technology is crucial to the development of these vehicles, the U.S. Department of Energy (DOE) has funded research by universities, federal laboratories, and the private sector over several decades on a variety of new types of batteries. Automakers have also invested substantial amounts in research.

As manufacturers have brought hybrid, plug-in hybrid, and fully electric vehicles to market, U.S. policymakers have become concerned about the development of an electric vehicle supply chain in the United States. This report examines the nascent battery manufacturing industry and considers efforts to strengthen U.S. capacity to manufacture batteries and battery components for hybrid and electric vehicles.

HOW DOES A TRADITIONAL AUTOMOBILE ENGINE WORK?

For the last 100 years, Americans have primarily driven vehicles with internal combustion engines. An internal combustion (IC) engine burns fuel inside a combustion chamber when a mix of fuel and air is sprayed into it.[2] The mixture is compressed by a piston while a spark plug produces a spark that ignites the fuel. The resulting combustion, and the expanding gases, drives the piston back down. The piston is connected to a crankshaft which, in turn, powers the axles and propels the vehicle. See **Figure 1** for a cross-section diagram of part of an IC engine.

USING THE INTERNET TO LEARN ABOUT ELECTRIC VEHICLES

When you see a text box in this report, it indicates an Internet video resource that will be helpful in understanding dimensions of the battery industry, such as how lithium is mined. The box will give a short summary of the contents of the video. Paste or type **the footnote URL** in your browser to watch the video.

Most modern vehicles use either gasoline or diesel as a fuel source because they are energy dense and inexpensive. Gases are a byproduct of the combustion. The engine's exhaust valves remove them from the cylinder and send them on to the car's exhaust system. The engine's heat, another byproduct of the combustion process, is the source of a vehicle's heating system in the winter.

A critical element in a car's engine operation is the battery. When a driver turns the key in the ignition, the battery's stored energy is drawn down, powering the electric engine starter and thereby cranking the engine.

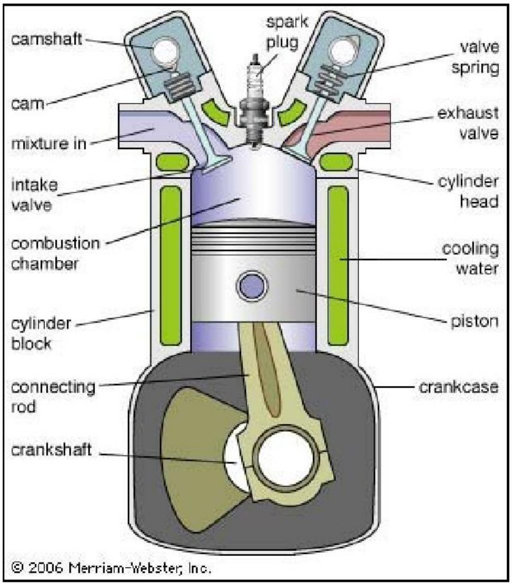

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Figure 1. Major Parts of an Internal Combustion Engine.

BATTERY TECHNOLOGIES

Batteries are a form of energy storage. They store and release energy through electrochemical processes. All battery technologies have two fundamental characteristics that affect battery design, production, cost of operation, performance, and durability:

- *Power density* is the amount of energy that can be delivered in a given period of time, affecting how fast a vehicle accelerates, and
- *Energy density* is the capacity to store energy, affecting the range a vehicle can travel.[3]

There is generally a trade-off between these two characteristics: some battery technologies have higher power density with a correspondingly lower energy density and vice versa. For vehicle applications, it is desirable to have *both* high power density and high energy density to compete with the high power and energy density of gasoline and other petroleum-based fuels. Battery alternatives to gasoline power have so far not achieved this parity and are heavy, large in size, and costly.

The first rechargeable lead-acid battery[4] was invented in France in 1859.[5] By the 1880s, French inventors improved the design, which in turn enabled the development of new types of electric automobiles at the beginning of the 20th century. Auto manufacturers, however, soon discovered that the lead-acid battery is better suited for supporting IC engines than for powering vehicles.

There are a number of reasons why this 19th-century technology has been the battery of choice around the world for so long. Lead-acid batteries are simple, inexpensive to manufacture, and based on a technology that is widely understood and easily duplicated. Relatively small in size, the batteries fit easily in the engine compartment, are durable and dependable, and require virtually no maintenance. Most importantly, they provide sufficient bursts of energy to start engines, while recharging over many cycles. In addition, 98% of lead-acid batteries are recycled, among the highest recycling rates for any manufactured product, thus minimizing the environmental impacts of disposal.

The typical automotive lead-acid battery is encased in a durable plastic casing. It generates 12 volts of electricity through six interconnected compartments (called cells), each of which contains 16 metal plates, set in an electrolyte solution of water (65%) and sulfuric acid (35%). The internal cell plates and separators are shown in Figure 2. The positive anode side of each plate is coated in lead oxide; the negative cathode side in lead. As electrons move from the anode, they generate up to 2 volts of electricity within each cell. The cells are arranged in a series so that the electricity passes from one cell to the other, making the charge additive. By the time the charge has passed through each of the six cells, 12 volts of electricity are discharged through the terminals on the top of the battery to start the car and run the other automotive components.

HOW A TRADITIONAL CAR BATTERY WORKS

Most cars use lead-acid batteries, and they are one of the important components in any vehicle. Understanding how a lead-acid battery works in today’s vehicles is a good foundation for understanding how other types of batteries function in hybrid and electric vehicles. This Internet video shows how the chemicals in the battery generate electricity and the use of that energy to ignite the engine and operate windshield wipers, CD players, and other accessories. The video also shows how the internal combustion engine recharges the lead acid battery so it remains ready to crank the car every day.[6]

Source: Reprinted with permission from Exide Technologies.

Figure 2. The Lead-Acid Battery Showing Internal Components.

Once the gasoline-powered engine is started, it not only powers the pistons in the engine, thereby moving the car forward, but through the alternator[7] it also provides recharging for the battery. In this process, the chemical process that created electricity is reversed: a flow of electrons moves backwards from the cathode toward the anode, restoring the chemicals on the plates to their original position. This ongoing process of charging and recharging the battery takes place automatically as the car is being driven.[8]

The lead-acid battery has been the standard battery technology for most of the past century, but because of its low energy density, it is poorly suited for electric vehicles. A 2010 DOE report noted that batteries have been "too costly, too heavy, too bulky and would wear out too soon."[9] Were a group of lead-acid batteries placed in a hybrid or all-electric car, they would take up an inordinate amount of space and would add exceptional weight to a car.[10] Accordingly, new kinds of batteries are being developed that offer higher power and energy densities for these types of vehicles.

What Are the Alternatives?

Given the shortcomings of lead-acid batteries, researchers have sought better battery technologies since the 1970s. One of the first commercially feasible technologies[11] automakers adopted was the nickel metal-hydride (NiMH) battery. Because it has greater energy density and is lighter than a similarly powerful lead-acid battery, NiMH batteries became the choice for early hybrid vehicles. They are used in many hybrid vehicles today, including the Toyota Prius, Honda Insight, and Ford Escape Hybrid.[12] Toyota announced in 2009 that after testing alternatives, it would continue using NiMH batteries in most of its hybrid vehicles.[13]

A second technological approach involves improvement of lead-acid batteries.[14] Recent federal research grants were given to two U.S. lead-acid battery manufacturers to advance use of lead-carbon in batteries and to further work on an "ultrabattery" that could replace NiMH with a more efficient, lower-cost alternative.[15]

A third technology is the "Zebra"[16] battery, using sodium-nickel chloride chemistry. These produce 50% more energy than NiMH and, according to some manufacturers, as much as some lithium-ion batteries.[17] These so-called "hot" batteries have operating temperatures up to 360 degrees (F) and reportedly perform well in very hot and very cold climates.[18]

Table 1. Lithium-Ion Battery Chemistries in Passenger Cars Some Major Lithium-Based Technologies in the United States.

Types of Cathodes	Developers	Vehicle Application
Nickel, cobalt, and aluminum (NCA)	Johnson Controls-Saft	Mercedes Benz S400 Blue Hybrid
Manganese	LG Chem, NEC	Chevrolet Volt, Nissan Leaf
Iron-nano-phosphate	A123 Systems	Fisker Karma[a]
Nickel, manganese, and cobalt	EnerDel	THINK City electric vehicle[b]

Source: "Electrification Roadmap," Electrification Coalition, November 2009, and data supplied by manufacturers.

Notes: Each technology is paired with lithium.

a. Fisker Karma is planned for commercial sale beginning in 2Q 2011.

b. THINK City vehicles have been initially sold for fleet use by the state of Indiana.

The most prominent major new battery technology is based on lithium, a naturally occurring and lightweight metal[19] used in laptop computer batteries. Li-ion batteries have high energy and power densities. Because lithium is lightweight, it can be fabricated into large battery packs for use in hybrid and electric vehicles. An important characteristic of lithium is that it is reusable and can be extracted from depleted batteries and recycled for use in new batteries.

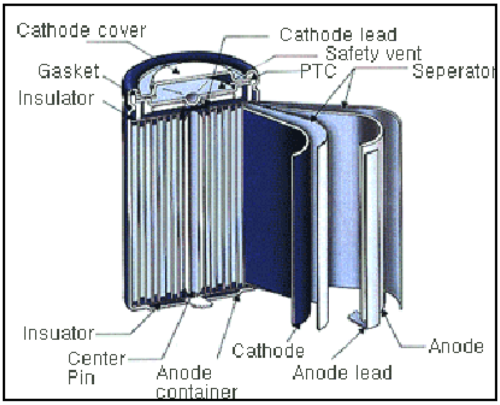
There are several types of lithium-based battery technologies available for commercial application; not all automakers are using the same approach. While the types of chemistries[20] shown in **Table 1** differ, they have similar energy and power densities.

The Basics of Lithium-Ion Batteries

Li-ion batteries share five basic structural components with lead-acid batteries: cathode, anode, separator, electrolyte solution, and a durable case. Li-ion batteries, like many other batteries, also have a safety structure in light of potential chemical leakage and flammability. Figure 3 shows a cross-section of a lithium-ion cell in cylinder form. An anode is the point on the battery where current flows in from outside; the cathode is the point where the current flows out of the battery. During electrical discharge, lithium in the anode is ionized and emitted, along with electrons, into the electrolyte. The ions and electrons move through the porous separator and into the lithium metal oxide cathode, where the electric current they have produced is discharged.

Li-ion battery cells can also be manufactured in rectangular shapes using gel as the electrolyte, and then encased in laminated film. Rectangular cells can be more efficient because their shape means more finished cells can be assembled in a battery pack, increasing the density of the battery.[21] The main parts of the cell and their functions are the following:

- *Cathode.* As described in **Table 1**, there are four major types of materials that can be used in making the cathode of a Li-ion cell. Regardless of the material, it is pasted on aluminum foil and pressed into a suitable shape and thickness.
- *Anode.* Graphite and carbon are generally used as the basic materials and are pasted on copper foil, then pressed into shape.
- *Electrolyte*. A mixture of lithium salt and organic solvents, such as ethyl methyl carbonate or propylene carbonate, the electrolyte increases the mobility of Li-ions to improve battery performance. Lithium polymer batteries use a viscous gel as the electrolyte to reduce the chance of leaks, which are more likely with liquid solvents.
- *Separator.* This is a porous membrane that prevents the cell's anode and cathode from coming into contact with each other. Made of either polyethylene or polypropylene, it also provides a safety function, purposely melting down and preventing ion transfers if a cell heats up accidentally.
- *Safety elements*. Li-ion batteries can overheat, so they are built with safety vents, thermal interrupters, and other features, such as a center pin to provide structural stability, to prevent short circuits. Lead-acid and NiMH batteries are less prone to short-circuiting because their electrolyte solution is not flammable. In rare cases when a Li-ion battery does short-circuit, battery temperatures can increase by several hundred degrees in a few seconds, potentially leading to a chain reaction that could destroy the battery and cause a fire.[22] Automakers also build a computer-controlled, liquid thermal cooling and heating system to maintain battery temperatures in a safe range and to monitor other elements of the battery's performance.[23]
- *Canister.* A steel or aluminum can houses each Li-ion cell. The cells are assembled into a battery pack for final use. The Chevrolet Volt, for example, contains 288 rectangular cells in its six-foot-long battery pack.[24]



Source: Lowe, Marcy; Tokuoka, Saori; Trigg, Tali; and Gereffi, Gary, "Lithium-ion Batteries for Electric Vehicles: The U.S. Value Chain," Duke University Center on Globalization, Governance & Competitiveness, November 4, 2010, p. 32.

Figure 3. Cross-Section of a Cylindrical Li-ion Cell.

Battery packs containing Li-ion cells are much larger than a conventional lead-acid battery. In the Chevrolet Volt, the battery pack is 6 feet long, weighs 435 pounds and is arranged in a T-shape that sits under the center of the passenger cabin, as shown in Appendix B.

Automakers have not disclosed the costs of the Li-ion batteries they use. As discussed later in this report, the batteries reportedly cost from $375-$750 kWh,[25] making a 16 kWh battery cost as much as $12,000. Fully electric vehicles with a longer driving range would need as much as 35 kWh, meaning that the batteries alone would cost more than many vehicles now on the road.[26] To travel 300 miles on battery power, it is estimated that vehicles would need a capacity of 100 kWh of stored electric power.

The Li-Ion Battery Supply Chain

Because they are lightweight and have relatively high energy intensity, Li-ion batteries have been used predominantly in a range of small consumer products that are manufactured mainly in Asian countries, so many Li-ion battery manufacturers have located production in Asia.[27] It has been estimated that Japan and South Korea hold about 80% of the global market share of advanced Li-ion batteries; China, 12%; others, nearly 6%; and the United States, about 2%.[28] Present demand for Li-ion vehicle batteries is low, and market shares could change significantly in the next decade if demand for electric and plug-in hybrid vehicles increases.

The potential demand for Li-ion automobile batteries may encourage creation of a domestic battery supply chain. In the American Recovery and Reinvestment Act of 2009 (ARRA, P.L. 111-5), Congress sought to encourage this development with $2.4 billion of grants for battery manufacturing facilities.

There are several market factors that favor the creation of a domestic supply chain. First, most U.S. auto plants practice just-in-time manufacturing, with key suppliers located near the assembly plants they supply. Automakers will want their Li-ion battery suppliers near their plants as well. In addition, the heavy weight of large Li-ion batteries for cars and light trucks makes it more cost-effective to assemble those batteries near the motor vehicle assembly plants where they will be used, rather than transporting them for thousands of miles.

The Li-ion battery assembly plants, however, are only the final link in a lengthy supply chain that includes research and development, raw material search and mining, manufacture of equipment to make Li-ion batteries and cases, assembly of the batteries and electronics themselves, marketing, financing, shipping, and customer service. Much of this supply chain did not exist in the United States prior to the passage of ARRA.

A recent report on the Li-ion battery supply chain by Duke University's Center on Globalization, Governance & Competitiveness (CGGC)[29] divides the Li-ion supply chain into four levels. Tier 1 suppliers are generally larger firms that directly supply the automakers. Tier 2 and 3 suppliers often supply the Tier 1 supplier with components. CGGC found that as of November 2010 there were

- five Tier 3 suppliers, firms that are engaged in producing basic materials used in Li-ion batteries;
- 29 Tier 2 suppliers, firms that make cell components and electronics domestically;
- 21 Tier 1 suppliers, firms that now have or plan to have final Li-ion battery assembly facilities in the United States; and
- one company engaging in Li-ion recycling.

Tier 3 Suppliers

The United States currently "holds a strong supply position"[30] in lithium compounds produced by Tier 3 suppliers, as well as electrolyte solutions and graphite used on anodes, according to the Duke study. Two of the world's largest suppliers of lithium are U.S.-based FMC Lithium and Chemetall Foote, a division of Rockwood Holdings. Chemetall alone supplies over a third of all lithium used in the world, sourcing it from brine deposits in Chile and ore from a mine in North Carolina.[31]

According to the Mineral Information Institute, "most lithium is recovered from brine, or water with a high concentration of lithium carbonate. Brines trapped in the Earth's crust (called subsurface brines) are the major source material for lithium carbonate. These sources are less expensive to mine than rock such as spodumene, petalite, and other lithium-bearing minerals."[32] While U.S. firms have a strong foothold at this level of the supply chain, most of the raw material comes from abroad.

> It is estimated that the United States has approximately 760,000 tons of lithium. The resources in the rest of the world are estimated to be 12 million tons. The United States is the world's leading consumer of lithium and lithium compounds. The leading producers and exporters of lithium ore materials are Chile and Argentina. China and Russia have lithium ore resources, but it is presently cheaper for these countries to import this material from Chile than to mine their own.[33]

HOW LITHIUM IS MINED

The most efficient way to produce lithium is through brine pools. The world's largest such deposits are in the Salar de Atacama desert in Chile. The lithium brine is pumped out of underground caverns and, in large surface ponds, the sun is used to evaporate the other salts. Half of the world's lithium is sourced from this one desert in Chile. An executive with a U.S. company, Rockwood Holdings, is interviewed in a video segment from CBS News on how lithium is mined in Chile.[34]

Industry analysts say there is no shortage of lithium in the foreseeable future and that by 2020, there may be an excess supply of it, driving down prices and undermining investments by current producers.[35]

In addition to lithium, manganese, nickel, cobalt, copper, and aluminum are used in different forms in making Li-ion batteries. While there are diverse sources for most of these minerals, some are concentrated in a few locations that could have implications for supply or pricing. For example, more than a third of the world's production of cobalt comes from the Democratic Republic of Congo and some rare earth minerals used in producing electric vehicle components are mined primarily in China.

U.S. suppliers have strong positions in the manufacture of several other basic materials used in battery manufacturing. Novolyte makes electrolytes at its Baton Rouge, LA, plant and Honeywell is poised to become the first U.S. producer of lithium salt for use in electrolytes.[36] Future Fuel Chemical in Batesville, AR, is apparently the only U.S. producer of graphite components used in anodes.

Tier 2 Suppliers

Moving up the supply chain, the Tier 2 suppliers provide components and chemicals for Li-ion cells, as well as electronics used in the final battery packs (see Table 2). U.S. firms included in this part of the supply chain are Celgard, the world's third-largest producer of separators, as well as DuPont and Applied Materials. ConocoPhillips and Superior Graphite produce active materials and binders used for anodes. 3M, A123 Systems, Dow Kokam, and SouthWest NanoTechnologies make active materials, binders, and carbon electric conductors for cathodes.

Electronics developed for Li-ion batteries are similar to those used in consumer goods, and are used to manage various battery functions. They check the voltage, cell balance and monitor and report charging status. Chips are also used to monitor and regulate the temperature of the Li-ion battery so it does not overheat. Texas Instruments, Atmel, and Maxim Integrated Products are among the electronics and controls companies that produce electronic components. Other components used in the battery include the steel or aluminum can which houses the Li-ion cell (made by H&T Waterbury); insulators; safety vents; gaskets; and center pins.

Tier 1 Suppliers

Tier 1 suppliers put all the pieces together into a battery. The cell and battery-pack manufacturers are the most visible part of the U.S. electric battery supply chain, but this stage has been the weakest link until recently, as only one company—Indiana-based EnerDel—has operated a domestic high-volume anode and cathode coating and cell manufacturing facility. To date, most U.S. pack manufacturers import cells. For example, the Li-ion cells used in the in GM Volt's batteries are made by LG Chem in South Korea, shipped to Michigan, and made into batteries there.[37] LG Chem is duplicating its South Korean facilities at a new plant in Michigan.[38]

Table 2. Leading Domestic Suppliers to Li-ion Battery Manufacturers Selected Tier 2 Producers.

Tier 2 Supplier	Facility Location
Celgard	Charlotte, NC
DuPont	Chesterfield County, VA
Applied Materials	Santa Clara, CA
ConocoPhillips	Houston, TX
Superior Graphite	Bedford Park, IL
3M	St. Paul, MN
A123 Systems	Livonia, MI
Dow Kokam	Midland, MI
SouthWest NanoTechnologies	Norman, OK
Texas Instruments	Dallas, TX
Atmel	San Jose, CA
Maxim Integrated Products	Sunnyvale, CA
H&T Waterbury	Waterbury, CT

Source: Marcy Lowe et al., “Lithium-ion Batteries for Electric Vehicles,” pp. 45-47. See note 29.

This is the part of the supply chain that has received significant federal subsidies through ARRA to jump-start U.S. production, as described in the following section. The additional firms that have begun to build Li-ion manufacturing capacity include Johnson Controls, A123 Systems, Boston Power, Compact Power (LG Chem’s U.S. facility), and Dow Kokam.

These companies follow a variety of strategies for manufacturing in the United States. The Duke report asserted, “typically, non-U.S, battery pack manufacturers keep high value-added activities like R&D, engineering and design in the home country. For example, Compact Power’s high-value activities take place at its parent company’s location in South Korea. Similarly, the patents for most JCS [Johnson Controls-Saft] Li-ion battery products are held by Saft [a French company].”[39] A123 Systems, a U.S. company, does its research and engineering in the United States. Until recently, it produced its cells at plants in South Korea and China, but it now also has two plants in Michigan doing cell assembly and making anode and cathode coatings.

These U.S-based facilities will be competing with Asian facilities that have been successfully making and marketing large-volume Li-ion batteries for consumer products for decades, including BYD, Hitachi, NEC, Panasonic, Samsung, and Toshiba. Makers of Li-ion vehicle batteries will need to achieve high-volume production to realize economies of scale and drive unit costs down. Achieving adequate volume may be a challenge for the Tier 1 suppliers in the United States in light of a highly competitive marketplace for battery packs.

A 2010 report by researchers at the Massachusetts Institute of Technology highlighted the central role of scale in vehicle electrification:

> Manufacturing is key to achieving a commercially successful EV battery pack. Low cost is only achieved in large-volume, highly automated factories. This raises two issues. Successful development of EVs requires attention to both R&D and manufacturing of battery systems. Understanding possible economies of scale in manufacturing is an important aspect of battery technology development since manufacturing cost is decisive in the ultimate economics of EVs. Second, battery manufacturing will not necessarily occur in the country that creates the battery technology. This is an especially vexing political question in the US where it is widely believed, perhaps correctly, that high-technology manufacturing of products such as batteries is taking place abroad, especially Asia, despite low labor content. Both issues have implications for the government role in supporting EV development.[40]

The Role of the Automakers

The Tier 1 suppliers deliver batteries to the automakers for final assembly into vehicles. The automakers' role is quite different than that with traditional lead-acid batteries, which are simply dropped into a vehicle's engine compartment and connected to the electrical system. In manufacturing hybrid and fully electric vehicles, the automakers provide additional critical, proprietary technologies that mesh the battery's output with the vehicle's overall operation. GM has highlighted one such technology application:

> "Three different systems are used to regulate the temperature of the coolant," said Bill Wallace [GM's Director of Global Battery Systems]. "When the Volt is plugged in and charging in cold weather, an electric heater at the front of the battery pack is used to warm the coolant and pre-heat the battery. During normal operations, the coolant is passed through a heat exchanger at the front of the car,

> while a chiller in the air conditioning circuit can be used to dissipate heat from the battery when temperatures really climb."
> The management system monitors feedback from 16 thermal sensors arranged throughout the battery pack to maintain a spread of no more than 2 degrees centigrade from the optimal temperature across the pack.[41]

Automakers are integrally involved in the design and production of Li-ion batteries for their vehicles. As GM noted in a recent report, "the Volt's battery pack design is directly coupled with the vehicle design to assure complete integration between the battery pack and the vehicle."[42] This means that the automaker's decision as to which battery to procure will be in effect for a prolonged period, perhaps the life of the vehicle model, as a battery designed for one vehicle may not function optimally in another. Some automakers have entered joint ventures or partnerships with battery manufacturers. The batteries for the Nissan Leaf all-electric vehicle are sourced from a Nissan partnership with NEC, for example, and Toyota has a similar battery joint venture with Panasonic. These arrangements may benefit the battery manufacturers by permitting large-volume production, but may also tie the battery manufacturer's fate to the success of a single vehicle manufacturer.

U.S. automakers appear to have rejected such corporate alliances, deciding instead to shop for batteries for particular models. For example, General Motors sought competitive bids before selecting South Korea-based LG Chem for its Volt Li-ion battery, reportedly over U.S.-based A123 Systems. According to an investment report by Goldman Sachs, LG Chem's "principal advantage is manufacturing scale and experience."[43]

THE BATTERY MANUFACTURING PROCESS

Li-ion batteries have generally been produced in Asia, near manufacturing sites for battery-dependent portable consumer products. But the transition from small, consumer-goods batteries to larger batteries for motor vehicles[44] may well open the door for new entrants into the industry. In the motor vehicle industry, according to one analyst, "extended cycle life, high specific energy, and safety in extreme conditions—necessitate much tighter tolerances on material and manufacturing specifications, and often require a fundamental rethinking of core battery technology."[45] This implies that the companies that have been most successful in manufacturing Li-ion batteries for consumer products will not necessarily dominate the automotive market.

The first step in manufacturing a battery is to procure the lithium, which is mined primarily in Chile. The mineral is refined into a white powder (lithium carbonate) at Chilean plants and shipped as either a powder or as 11-pound ingots to Tier 2 or 3 manufacturers.

The Tier 2 and 3 suppliers convert the ingots or powder into lithium metal that is used in battery cells. This is a highly automated process requiring great precision. The manufacturers apply an extrusion process to the ingot and flatten it into a more manageable piece of metal which is 1/100th of an inch thick and 650 feet long. Eventually, the metal, rolled even thinner (1.25 miles long), will produce over 200 batteries. Because the lithium metal strip can stick to itself, a soft film is laminated to it so it can be further wound into spools.

At this stage, the lithium is divided into individual cells, heated at a high temperature for 90 minutes then tested for electrical transmission capabilities. A punch machine cuts out cells in the sizes needed for their application (automobiles, cell phones, laptops, etc.)[46] It has been estimated that 70% of the value-added in making Li-ion batteries is in the development and manufacture of the cell itself (compared with, for example, only 15% in the assembly of the battery and 10% in electrical and mechanical components).[47]

The individual cells are packaged carefully and shipped to a Tier 1 fabrication plant where they are sprayed with molten metals that will establish the anodes and cathodes of the battery cell. The cathodes, as shown in **Table 1**, are especially important in the battery function, because there are different options for their chemical composition and they have unique characteristics which each manufacturer has developed and may have patented. Some cathode manufacturers may partner with companies that specialize in producing advanced cathode materials. As the battery industry develops, it is likely that the Tier 2 battery component plants will be built adjacent to the Tier 1 facilities, as geographic proximity is seen as a competitive advantage in the supplier-automaker relationship.[48]

Tier 1 manufacturers and automakers assemble the individual cells, fabricate the modules, and assemble all components from Tier 2 and 3 suppliers into battery packs ready for placement in a motor vehicle. Battery packs have 250-500 cells; A123 Systems forecasts that it will produce 1 million cells a month by the end of 2011.[49] GM chooses to do the final battery pack assembly at its Brownstown, MI, plant, giving it more control over how the battery pack interacts with the vehicle's overall power system. As one analyst noted, "the fact GM is keeping 100% of the battery integration in-house illustrates the centrality of the battery in electric vehicles."[50]

ARRA AND THE BATTERY SUPPLY CHAIN

In 2009, ARRA provided $2.4 billion in stimulus funding to support the establishment of Li-ion battery manufacturing facilities in the United States.[51] The Obama Administration asserts that ARRA investments may lower the cost of some types of electric car batteries by 70% by the end of 2015, enabling the production of as much as 40% of the world's advanced vehicle batteries in the United States.[52] In August 2009, DOE announced that it would fund 48 new advanced battery manufacturing and electric drive vehicle projects for PHEVs and EVs in over 20 states, stating,

> the grantees were selected through a competitive process conducted by DOE and are intended to accelerate the development of U.S. manufacturing capacity for batteries and electric drive components as well as the deployment of electric drive vehicles to help establish American leadership in developing the next generation of advanced vehicles.[53]

DOE provided $1.5 billion in grants to accelerate the development of a domestic battery supply chain, including

- $28.4 million to develop lithium supplies;
- $259 million to produce Li-ion cell components such as cathodes, anodes, separators, and electrolyte solution;
- $735 million to make cells using diverse chemistries such as iron phosphate, nickel cobalt metal, and manganese spinel;
- $462 million for pack assembly facilities; and
- $9.5 million for a lithium recycling facility.

Appendix A provides detail on these grants. The five largest grants, totaling nearly $980 million—approximately two-thirds of total grant funding—went to the companies in Table 3.

Table 3. Five Largest Recipients of ARRA Electric Storage Funding in Millions of U.S. Dollars.

Company	Amount	Purpose
Johnson Controls	$299.2	Produce nickel-cobalt-metal battery cells and packs and cell separators
A123 Systems	249.1	Produce iron-phosphate cathode powder and electrode coatings; fabricate cells and battery packs
Dow Kokam	161.0	Produce manganese cathodes and lithium-ion batteries
Compact Power	151.4	Produce separators and lithium-ion polymer batteries cells
EnerDel[a]	118.5	Produce lithium-ion cells and packs

Source: *Energy Storage Research and Development, Annual Progress Report 2010,* U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, January 2011, Appendix A.

Notes: Compact Power is the U.S. subsidiary of LG Chem. With the exception of Indiana-based EnerDel, these top recipients plan production in Michigan.

a. EnerDel is a wholly owned subsidiary of Ener1, Inc.

The remaining $900 million in ARRA funding for new electric battery development was allocated for two related goals: (1) $500 million was provided for U.S. production of electric drive components for vehicles, including electric motors, power electronics, and other drive train components; and (2) $400 million for purchase of several thousand PHEVs for demonstration purposes, installation of a charging station network, and workforce training related to transportation electrification.[54]

The Obama Administration argues that the ARRA spending has had an immediate impact in transforming the U.S. advanced battery industry. In a statement issued in January 2011, when Vice President Joe Biden visited the Ener1 battery manufacturing facility in Mt. Comfort, IN, the U.S. Department of Energy (DOE) said that ARRA would increase U.S. advanced technology battery manufacturing capability from two plants and a 2% global market share to more than two dozen manufacturers and a projected 40% of the world's EV batteries by 2015, and that it would cut the cost of batteries in half by 2013.[55]

In his State of the Union address in January 2011, President Obama urged budget increases in the electric vehicle and storage battery programs. Specifically, the President's budget for FY2012 calls for Congress to enact three initiatives:

- Convert the existing $7,500 tax credit for electric vehicles to a federally funded rebate up to the same amount. The Administration argues that a rebate would encourage more Americans to buy electric vehicles if they did not have to wait to file their tax return to realize the savings. Automobile dealers would be an integral part of this plan as the rebates would be made available at point of purchase.
- Raise R&D investment in electric drive, battery, and energy storage technologies. The budget proposes to increase funding for the Vehicles Technologies program by 93%: from $304 million to $588 million, with a goal to "move mature battery technologies closer to market entry through the design and development of advanced pre-production battery prototypes."[56]
- Provide grants to 30 communities to invest in electric vehicle infrastructure, such as networks of charging stations, through the Vehicles Technologies program.

FEDERAL SUPPORT FOR BATTERY TECHNOLOGY R&D

Congress first acted to support electric and hybrid vehicle technologies in 1976, when it established a demonstration project that was to lead to the federal purchase of 7,500 electric vehicles.[57] The legislation was vetoed by President Gerald Ford on the grounds that it was premature to demonstrate vehicle technologies before adequate batteries had been developed, but Congress overrode his veto. This law initiated DOE's hybrid and electric vehicle research and development program. Recognizing that advanced technology vehicles were only as good as the batteries that would propel them, DOE began a research program to improve existing—that is, lead acid—battery technology and to study what were then advanced concepts of battery chemistry, such as sodium sulfur and lithium iron metal sulfides.

A number of electric demonstration vehicles were produced in the following years by Ford, General Motors, and American Motors, but Congress realized in 1978 that producing so many demonstration vehicles quickly was unrealistic. It stipulated a new schedule, mandating the introduction of only 200 vehicles in 1978, 600 in 1979, and more in the 1980s. However, President Ronald Reagan cancelled the program in 1981,[58] basing the decision in part on a critical 1979 General Accounting Office report. GAO asserted commercialization would require a major effort to improve electric vehicle technology, strengthen the electric vehicle industry, establish a new market, and create an infrastructure to support it. It found that the private sector demonstration project was premature and urged refocusing of government R&D.[59]

In subsequent years, DOE continued research on vehicle energy storage options. In 1990, California mandated that zero emission vehicles be sold by major automakers, ushering in new interest in hybrid and electric vehicles. The Energy Policy Act of 1992 (P.L. 102-486) directed DOE to develop a research, development, and demonstration project for fuel cells and electric vehicles.

DOE has provided support to the research programs of the U.S. Council for Automotive Research (USCAR), which was established in 1992 as the U.S. motor vehicle industry's research consortium on advanced vehicles.[60] USCAR houses the U.S. Advanced Battery Consortium (USABC), focused on research and development of battery technologies.[61]

Partnership for a New Generation of Vehicles

In 1993, the Clinton Administration expanded the scope of advanced vehicle research by establishing the Partnership for a New Generation of Vehicles (PNGV).[62] This initiative was a public-private partnership between the federal government and USCAR. Its goals were to (1) leverage federal and private sector resources to develop advanced manufacturing technologies, within 10 years; (2) produce near-term improvements in automobile efficiency, safety and emissions; and (3) triple vehicle fuel efficiency from the average 1994 level to 80 miles per gallon,[63] while still meeting all environmental regulations and keeping the cost affordable.

A top priority of the program was to develop advanced auto manufacturing technologies that would spawn production of vehicles with low gasoline consumption and emissions. PNGV officials believed that if such vehicles were attractive commercially, then they would sell in high volumes, driving down costs. While PNGV supported work on a broad range of manufacturing technologies and products, such as new lightweight materials and new fuels, a prominent aspect of the program was the decision of the automakers to seek to build diesel-powered, hybrid-electric vehicles (HEV) through this program. Consequently, PNGV's focus included research and development of advanced energy storage systems for use in the HEVs.

Battery research under PNGV was focused primarily on NiMH and Li-ion batteries because these technologies were thought to offer the best prospects for performance, cost, durability, and safety. In a review of PNGV in its final year of 2001, the National Research Council (NRC) of the National Academy of Sciences found that

> [t]he soundness of choosing these [NiMH and Li-ion] systems for development is confirmed by the substantial progress made by PNGV toward most of these targets and the commercial use by all Japanese HEVs of either NiMH or Li-ion batteries.[64]

But NRC also said that these new batteries were not ready for widespread use, noting that,

> despite significant progress, calendar life, cost, and safety remained concerns for Li-ion technology, which is receiving the bulk of PNGV'S battery R&D funds…. Nickel metal hydride HEV batteries have not quite met performance targets, and, as with Li-ion batteries, projected costs have exceeded targets by about a factor of three.

FreedomCAR and beyond

The Bush Administration revamped PNGV administratively, as there was no statutory basis for it. In its place, it established in 2002 a similar initiative with more of a focus on commercial as well as passenger vehicles and on fuel cell research: the FreedomCAR and Fuel Partnership within DOE.[65] USCAR was still the private sector partner, but other federal agencies that had been part of PNGV, such as the Department of Commerce, were no longer involved. In addition, five major oil companies, including ExxonMobil and Chevron, joined the research effort to develop more efficient IC engines focused on hydrogen fuel cells and, eventually, hybrid electric vehicles. Two utilities, DTE Energy (Detroit) and Southern California Edison, also joined the Partnership.

As with PNGV, the new initiative included an energy storage program, called "FreedomCAR and Vehicle Technologies," or FCVT. It built on the research base of predecessor programs with industry-government technical teams. About 61% of the federal research funding was spent on work at the national laboratories, 35% on industry research, and 4% on university and other types of research.[66] Its goal was to demonstrate that high-power Li-ion batteries will be able to meet the performance targets for hybrid electric vehicles. Over three-fourths of FCVT's spending was directed toward development of *high power density* batteries for near-term use in hybrid vehicles. The remainder supported long-term exploratory research to find the *high energy density* technologies for a second-generation Li-ion system that would be appropriate for use in electric vehicles.

The Obama Administration has continued DOE's Vehicle Technologies research and development program in addition to promoting battery manufacturing. Current research emphasizes reducing the cost and improving the performance of Li-ion batteries and assessing new materials for cathodes, such as manganese oxides and iron phosphates. These may eventually offer cheaper and more stable alternatives to lithium cobalt oxide, contributing to cost reductions for electric vehicles.

Table 4 shows federal spending on battery and battery-related research and development since 2002.

GROWTH PROSPECTS OF THE U.S. BATTERY INDUSTRY

The U.S. battery industry will grow only as fast as the hybrid and electric vehicle market. There has been significant interest in new types of vehicles, as shown by the list of current and future hybrid and electric vehicles in **Appendix C**. Despite this wave of new vehicle introductions, many auto industry analysts say the number of hybrid and electric vehicles that will reach the market will be relatively modest in the near term.

Table 4. Recent Funding for Energy Storage Research Annual Appropriations, in Millions of Nominal U.S. Dollars.

Fiscal Year	Amount
2002	$24.1
2003	21.6
2004	22.3
2005	22.5
2006	24.5
2007	40.9
2008	48.3
2009	69.4
2010	76.2

Source: U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy (EERE).

Table 5. Obama Administration Projected Annual Sales of Electric Vehicles.

2011	2012	2013	2014	2015
45,600	177,600	263,000	368,000	368,000

Source: "One Million Electric Vehicles by 2015: February 2011 Status Report," U.S. Department of Energy, p. 4.

President Obama has set a goal of having 1 million electric vehicles on the road by 2015. In February 2011, DOE issued a report stating that "leading vehicle manufacturers already have plans for cumulative U.S. production capacity of more than 1.2 million electric vehicles by 2015, according to public announcements and news reports."[67] DOE projections of vehicle sales between now and 2015 are shown in Table 5. These projections imply that electric vehicles will occupy a small share of the U.S. auto market, which has averaged 13.6 million sales per year over the last five years.[68] If the goal is met, electric vehicles would account for less than one-half of 1% of a total U.S. fleet that exceeds 250 million cars and light trucks.

The goal of 1 million electric vehicles sold by 2015 may be ambitious. It appears, for example, that the Administration anticipates much higher levels of Chevy Volt sales than anticipated by the manufacturer, General Motors.[69] A February 2011 report by a group of auto industry experts empanelled by the School of Public and Environmental Affairs at Indiana University contended that "the production intentions of automakers are currently insufficient to meet the 2015 goal, and even the current plans for production volume may not be met."[70] DOE itself acknowledged in February 2011, "while it appears that the goal is within reach in terms of production capacity, initial costs and lack of familiarity with the technology could be barriers." The increased support for electric vehicles proposed by the Administration is therefore necessary to help meet the goal, DOE said.[71]

In addition to the level of federal support, these other factors will influence the development of a domestic advanced battery industry:

- *Cost.* There is a consensus that the current cost of electric batteries is too high. The automakers have not said how much their batteries cost, but analysts' estimates run as high as $16,000, more than one-third of the total price of electric cars.[72] Battery costs are commonly expressed in kilowatts per hour (kWh). Recent reports indicate cost ranges of

$500-$600/kWh for the Volt battery, $375-$750/kWh for the Leaf, and $680/kWh for the Tesla Roadster.[73]

If these estimates are accurate, then the 16 kWh Volt battery would cost $8,000 to $9,600 and the 24 kWh Leaf battery would cost between $9,000 and $18,000.[74] If production of batteries were to increase substantially, then economies of scale could drive these costs down, as could research breakthroughs. The U.S. Advanced Battery Consortium has a mid-term target of $250/kWh and a longer-term goal of $100/kWh.

- *Charging.* Electric vehicles will need to be recharged as often as every day, depending on how far the cars are driven. Current charging applications using standard 110-volt household current can take over 12 hours. Homeowners can install more powerful charging stations at home, but a 220-volt charging station would still require a car to charge for six hours or more. At commercial 440-volt charging stations, a driver would have to leave the vehicle for 30 minutes if its battery is depleted. In addition, the driving range of an electric vehicle drops if many accessories, such as air conditioning, are used, potentially requiring car owners to calculate their recharging needs more frequently when they drive.
- *Range*. Many vehicles with IC engines can travel over 350 miles before needing a refill of gasoline. Vehicles with electric motors have a shorter range, which may cause some consumers to avoid purchasing them. The U.S. Environmental Protection Agency (EPA) estimates that the Leaf will travel 73 miles before recharging and the Volt, 35 miles. (The Leaf is an all-electric vehicle; the Volt also has a small gasoline tank that extends its total range to 379 miles). Ranges are lower if the heater or air-conditioning is used extensively, as the power for these accessories is drawn totally from the battery. However, improvements in regenerative braking systems, which provide power for the vehicle and simultaneously recharge the battery, may extend range.[75]
- *Price of gasoline*. Sustained high gasoline prices would be expected to spur stronger demand for fuel-efficient vehicles, including hybrid and electric vehicles.
- *Improved IC engine technology.* A number of low-cost vehicles with IC engines are coming on the market with fuel efficiency of 40 miles per gallon (mpg) or more. They include the Chevrolet Cruze, Hyundai Elantra, Ford Fiesta, and Ford Focus. The hybrid Toyota Prius is rated

at 51 mpg. The most fuel-efficient cars with IC engines sell from just under $14,000 to $23,000, well below the current cost of either the Volt or Leaf, even after the $7,500 federal tax credit.[76] Improved fuel efficiency in IC engines may reduce the attraction of electric vehicles.

- *Subsidies by other governments.* The U.S. government is not alone in wanting to establish a Li-ion battery supply chain. Governments in Japan, South Korea, and China are providing similar incentives. Japan is currently the leader in manufacturing of advanced automobile batteries, although its industry is modest given the low level of global demand.[77] South Korea has announced a $12.5 billion investment in the "Battery 2020 Project," which seeks to make that country the dominant battery manufacturer in the next decade. China has a similar national policy and is reportedly investing $15 billion over the next decade.[78]

  European manufacturers have generally favored further improvements in IC engines, and there is a greater acceptance of diesel engine fuel economy technology than in the United States. Europeans, however, are seemingly beginning to embrace electric vehicles. German Chancellor Angela Merkel recently said at an auto forum that "if we want to remain the world leader in automobiles, then we have to be at the forefront of electromobility."[79] Daimler's research director reiterated this theme, saying it would be "fatal" if Germany did not have Li-ion battery development and production.[80]

CONCLUSION

The United States is well on its way to building large parts of a domestic Li-ion battery supply chain, spurred by ARRA. As shown in Appendix C, nearly all automakers plan to launch electric vehicles in the next few years, and federal and private investments are adding increased capacity levels throughout the battery supply chain.

Although electric vehicles are still in their infancy, there may be a gap between the Administration's goal of having 1 million electric vehicles on the road by 2015 and consumer demand for such vehicles. Chevrolet and Nissan forecast 2011 sales of 10,000 Volt and Leaf vehicles, respectively. General Motors has further said it hopes to produce 60,000 Volt cars in 2012 while Nissan has forecast global production of 500,000 Leaf vehicles in the same year. In the first two months of 2011, Chevy sold only 602 Volts in the United

States, while Nissan sold just 154 Leafs.[81] Should this demand pattern remain in effect for the year, both manufacturers would fall well short of their modest U.S. sales targets.

Two major obstacles may stand in the way of the United States creating a significant electric vehicle industry based on a domestic electric battery supply chain. First, there is intense international competition, both in vehicles and in the batteries to power them. Whatever their long-run prospects, electric vehicles and batteries are unlikely to be profitable for manufacturers in the near term. The 2010 Duke University study called for additional federal and state support so that domestic firms will capture markets and build "brands of reliability, durability and safety,"[82] and several other academic panels have made similar recommendations. Given that capacity outstrips current demand for both vehicles and advanced batteries, the point at which a domestic battery industry could stand on its own, without federal support, cannot be predicted.

Secondly, to attain broader consumer acceptance and thereby build the scale to drive down production costs, battery technology needs to advance further to address cost, range and recharging issues. It remains uncertain that Li-ion batteries will be the ultimate solution. As a recent academic report asserted:

> Lithium-ion batteries may never have adequate energy density to independently power a household's primary multi-purpose vehicle. Although there have been significant improvements in battery technology since the 1990s, policymakers should consider a large increase in federal R&D investments into innovative battery chemistries, prototyping and manufacturing processes.[83]

Advanced battery manufacturing is still an infant industry whose technology and potential market remain highly uncertain. Its development in the United States is likely to depend heavily on how the federal government further addresses the challenges of building a battery supply chain and promoting advances in battery technologies.

APPENDIX A. ARRA AWARDS

Recovery Act Awards for Electric Drive Vehicle Battery and Component Manufacturing Initiative			
Applicant	**DOE Award (in Millions of Dollars)**	**Project Locations**	**Technology**
Cell, Battery, and Materials Manufacturing Facilities			
Johnson Controls, Inc.	$299.2	Holland, MI Lebanon, OR (Entek)	Production of nickel-cobalt-metal battery cells and packs, as well as production of battery separators (by partner Entek) for hybrid and electric vehicles.
A123 Systems, Inc.	$249.1	Romulus, MI Brownstown, MI	Manufacturing of nano-iron phosphate cathode powder and electrode coatings; fabrication of battery cells and modules; and assembly of complete battery pack systems for hybrid and electric vehicles.
KD ABG MI, LLC (Dow Kokam)	$161	Midland, MI	Production of manganese oxide cathode / graphite lithium-ion batteries for hybrid and electric vehicles.
Compact Power, Inc. (on behalf of LG Chem, Ltd.)	$151.4	St. Clair, MI Pontiac, MI Holland, MI	Production of lithium-ion polymer battery cells for the GM Volt using a manganese-based cathode material and a proprietary separator.
EnerDel, Inc.	$118.5	Indianapolis, IN	Production of lithium-ion cells and packs for hybrid and electric vehicles. Primary lithium chemistries include manganese spinel cathode and lithium titanate anode for high power applications, as well as

Table. (Continued)

Applicant	DOE Award (in Millions of Dollars)	Project Locations	Technology
			manganese spinel cathode and amorphous carbon for high energy applications. EnerDel is a subsidiary of Ener1, Inc.
General Motors Corporation	$105.9	Brownstown, MI	Production of high-volume battery packs for the GM Volt. Cells will be from LG Chem, Ltd. and other cell providers to be named.
Saft America, Inc.	$95.5	Jacksonville, FL	Production of lithium-ion cells, modules, and battery packs for industrial and agricultural vehicles and defense application markets. Primary lithium chemistries include nickel-cobalt-metal and iron phosphate.
Exide Technologies with Axion Power International	$34.3	Bristol, TN Columbus, GA	Production of advanced lead-acid batteries, using lead-carbon electrodes for micro and mild hybrid applications.
East Penn Manufacturing Co.	$32.5	Lyon Station, PA	Production of the Ultra-Battery (lead-acid battery with a carbon supercapacitor combination) for micro and mild hybrid applications.
Advanced Battery Supplier Manufacturing Facilities			
Celgard, LLC, a subsidiary of Polypore	$49.2	Charlotte, NC Aiken, SC	Production of polymer separator material for lithiumion batteries.
Toda America, Inc.	$35	Goose Creek, SC	Production of nickel-cobalt-metal cathode material for lithiumion batteries.

Table. (Continued)

Applicant	DOE Award (in Millions of Dollars)	Project Locations	Technology
Chemetall Foote Corp.	\$28.4	Silver Peak, NV Kings Mtn., NC	Production of battery-grade lithium carbonate and lithium hydroxide.
Honeywell International Inc.	\$27.3	Buffalo, NY Metropolis, IL	Production of electrolyte salt (lithium hexafluoro-phosphate (LiPF6)) for lithium-ion batteries.
BASF Catalysts, LLC	\$24.6	Elyria, OH	Production of nickel-cobalt-metal cathode material for lithiumion batteries.
EnerG2, Inc.	\$21	Albany, OR	Production of high energy density nano-carbon for ultracapacitors.
Novolyte Technologies, Inc.	\$20.6	Zachary, LA	Production of electrolytes for lithium-ion batteries.
FutureFuel Chemical Company	\$12.6	Batesville, AR	Production of high-temperature graphitized precursor anode material for lithium-ion batteries.
Pyrotek, Inc.	\$11.3	Sanborn, NY	Production of carbon powder anode material for lithium-ion batteries.
H&T Waterbury DBA Bouffard Metal Goods	\$5	Waterbury, CT	Manufacturing of precision aluminum casings for cylindrical cells.
Advanced Lithium-Ion Battery Recycling Facilities			
TOXCO Incorporated	\$9.5	Lancaster, OH	Hydrothermal recycling of lithium-ion batteries.

Source: *Energy Storage Research and Development, Annual Progress Report 2010*, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, January 2011, Appendix A.

Notes: These grants total \$1.5 billion out of the \$2.4 billion appropriated through ARRA.

APPENDIX B. HYBRID VEHICLE BATTERY PLACEMENT

Source: General Motors; reprinted with permission from General Motors Company.

Note: The Li-ion battery is the T-shaped object that sits below the floor of the car and between the two front seats.

Figure B-1. Overview of the GM Volt.

APPENDIX C. CURRENT AND PLANNED HYBRID AND ELECTRIC VEHICLES IN THE U. S. MARKET

Hybrid Electric Vehicles (HEV):	**Extended Range Electric Vehicles (EREV):**
2011 Mercedes E Class Hybrid 2011 Porsche Cayenne S Hybrid 2011 Toyota Camry Hybrid 2011 Toyota Prius V Hybrid 2011 Audi A8 Hybrid (likely introduction)	2010 Chevy Volt Extended Range EV **Plug-in Hybrid Vehicles (PHEV):** 2010 Fisker Karma S Plug-in Hybrid

Table. (Continued)

2011 BMW 5-Series ActiveHybrid
2011 Honda CR-Z sport hybrid coupe
2011 Lexus CT 200h Hybrid Hatchback
2011 Suzuki Kizashi Hybrid
2011 Audi Q5 Crossover Hybrid
2011 Hyundai Sonata Hybrid
2012 Ford C-MAX Hybrid
2012 Infiniti M35 Hybrid
2014 Ferrari Hybrid

Battery Electric Vehicles (BEV):

2010 Mitsubishi i
2010 Nissan LEAF
2010 Ford TRANSIT connect electric
2010 Tesla Motors Roadster Sport 2.5
2011 TH!NK City
2011 Coda Automotive Sedan
2011 Tesla Motors Model S
2011 Ford Focus electric
2011 BMW ActiveE
2012 Fiat 500 minicar
2012 Audi e-tron
2012 Honda Fit EV
2012 Audi R8 EV
2013 Mercedes SLS E-Cell AMG
2013 Volkswagen Golf Blue-e-motion
2013 BMW i3
2016 Tesla Motors EV

2011 BYD F3DM Plug-in Hybrid
2012 Toyota Prius Plug-in Hybrid
2012 Bright Automotive IDEA Plug-in Hybrid
2012 Ford Escape Plug-in Hybrid
2012 Ford C-MAX Energi
2013 BMW Vision
2013 BMW i8
2013 Cadillac Converj

Source: Electric Drive Transportation Association, vehicle announcements through January 25, 2011.

End Notes

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[1] Samaras, Constantine and Meisterling, Kyle, "Life Cycle Assessment of Greenhouse Gas Emissions from Plug-In Hybrid Vehicles: Implications for Policy," *Environmental Science and Technology*, April 5, 2008, http://pubs.acs.org/ doi/full/10.1021/es702178s.

[2] Not all engines have *internal* combustion. For example, steam engines burn fuel outside the engine.

[3] Heavy batteries that take up a lot of space are not suitable for most light vehicles as space is needed for passengers, cargo and the other mechanical and electronic components. Battery density is measured in both volume (kilowatt hours/liter, kWh/l) and weight (kilowatt hours/kilogram, kWh/kg) terms.

[4] Benjamin Franklin is often credited with developing the term "battery" for referring to a group of charged glass plates, borrowing a military term for weapons that operate together as one unit. He developed such a battery that gathered an electrical charge and stored it until discharge. "'Electrical Battery' of Leyden Jars, 1760-1769," Franklin and Marshall College, The Benjamin Franklin Tercentenary, http://www.benfranklin300.org/frankliniana/result.php?id=72&sec=0.

[5] "Lead-Acid Battery Information," Battery Council International, http://www.leadacidbatteryinfo.org/resources.htm.

[6] To access the video on how a lead-acid battery works, copy or type the following link into a browser window: http://www.youtube.com/watch?v=4IgHj2Uim_0 (viewed on March 22, 2011).

[7] The alternator is an important intermediary in the engine that converts power from the gasoline engine into electrical energy to operate accessories and recharge the battery.

[8] If a motorist leaves a light on in the car or otherwise turns off the engine while continuing to draw down the battery, in time the battery will not function because the reversible charging described above will not occur. In this event, the battery will need to be charged by an external battery charger to restore its electricity-generating capacity.

[9] "The Recovery Act: Transforming America's Transportation Sector," U.S. Department of Energy, July 14, 2010.

[10] Lead-acid batteries weigh three to four times as much per kilowatt hour (kWh) as Li-ion. The Li-ion battery in the small THINK City car is 15% of the car's total weight; a comparable lead-acid battery pack would account for 50% or more of the car's weight. "Americas: Clean Energy: Clean Storage," Goldman Sachs, June 27, 2010, p. 11.

[11] This report focuses on battery technology, but the topic of energy storage includes research on ultracapacitors, which store electric energy in electric fields instead of electrochemically (as in batteries). Research funded by DOE and at major universities seeks to make ultracapacitors more compact through application of nanotechnology, and thereby more likely to be utilized as electric vehicle storage units in the future.

[12] The GM EV1, Toyota RAV4-EV and the Ford Ranger EV also used NiMH batteries when they were sold in California under that state's original Zero Emissions Vehicle mandate. (Although the original GM EV1 used lead-acid batteries, GM converted to NiMH in later models.) "Electrification Roadmap," Electrification Coalition, November 2009, p. 75, *http://www.electrificationcoalition.org/reports/EC-Roadmap-screen.pdf.*

[13] "Toyota Remains with Nickel after Lithium Prius Test," *Bloomberg.com*, September 14, 2009, http://www.bloomberg.com/apps/news?pid=newsarchive&sid=aI7Ov7Jyo2nU.

[14] In hybrid vehicles, the NiMH batteries provide power to the electric motor, while a lead-acid battery provides ignition and other starting functions.

[15] "The Potential Impact of Hybrid and Electric Vehicles on Lead Demand," International Lead and Zinc Study Group, March 2010, http://www.eurometaux.org/DesktopModules/Bring2mind/DMX/Download.aspx?TabID=57&Command=Core_Download&EntryId=304&PortalId=0&TabId=57 and East Penn Manufacturing Inc., http://www.dekabatteries.com/default.aspx?pageid=1372.

[16] It is called a Zebra battery because the initial work on this form of battery chemistry was conducted by a South African in 1985 as part of a research program dubbed the Zeolite Battery Research Africa project, or ZEBRA.

[17] The energy (by weight) of NiMH batteries is 30-80 Wh/kg; for Zebra batteries it is 100 Wh/kg, for lithium-cobalt oxide batteries it is 100 Wh/kg and for lithium-phosphate, 150 Wh/kg. "Cell Chemistry Comparison Chart," Woodbank Communications, http://www.elecropaedia.com, http://www.mpoweruk.com/specifications/comparisons.pdf.

[18] The Norwegian electric vehicle company THINK produces small cars and delivery vehicles; it offers both zebra and Li-ion battery options for its vehicles, http://www.thinkev.com/The-THINK-City/Charging/Batteries.

[19] In chemistry's periodic table, lithium is the lightest metal.

[20] These four lithium-based technologies are described in "Electrification Roadmap," Electrification Coalition, November 2009, pp. 84-86.

[21] Lowe, Marcy; Tokuoka, Saori; Trigg, Tali; and Gereffi, Gary, "Lithium-ion Batteries for Electric Vehicles: The U.S. Value Chain," Duke University Center on Globalization, Governance & Competitiveness, November 4, 2010, pp. 31-33.

[22] There have been a number of fires caused by Li-ion batteries, although none have been reported in automobiles. The U.S. Consumer Product Safety Commission has ordered numerous product recalls involving overheating Li-ion batteries in consumer goods, including in laptop and notebook computers, electric bicycles, wireless conference phones, and some types of remote-controlled toys. In 2006, Dell recalled over 4 million notebook Li-ion computer batteries after a series of publicized fires. "Dell Will Recall Batteries in PC's," *New York Times*, August 15, 2006.

[23] http://www.chevrolet.com/volt, http://www.chevrolet.com/volt/?seo=goo_|_2008_Chevy_Retention_|_IMG_Chevy_Volt_|_Exact_Match_Chevy_Volt_|_volt.

[24] Ibid.

[25] Kilowatt hour.

[26] By comparison, a 10 gallon tank of gasoline contains about 360 kWh of energy, according to Carnegie Mellon University researchers. Ching-Shin Norman Shiau, Constantine Samaras, Richard Hauffe, and Jeremy J. Michalek, "Impact of Battery Weight and Charging Patterns on the Economic and Environmental Benefits of Plug-In Hybrid Vehicles," *Energy Policy*, February 2009, http://www.cmu.edu/me/ddl/publications/2009-EP-Shiau-Samaras-Hauffe-Michalek-PHEV-Weight-Charging.pdf.

[27] Marcy Lowe et al., "Lithium-ion Batteries for Electric Vehicles," p. 6.

[28] Ibid., pp. 18-19.

[29] Marcy Lowe et al., "Lithium-ion Batteries for Electric Vehicles," p. 29.

[30] Ibid., p. 35.

[31] Chemetall also operates a small brine pool operation in Silver Peak, Nevada. South Korea and Japan, which do not have their own domestic lithium sources, have developed technology to extract lithium from sea water and plan to have such facilities operating in a few years. This would provide a third source for lithium (in addition to brine pools and ore) and could affect the world price for the mineral. "South Korea Plans to Extract Lithium from Seawater," http://www.smartplanet.com, January 20, 2011. It has been estimated that there are 230 billion tons of lithium in sea water. "Lithium Occurrence," Institute of Ocean Energy, Saga University, Japan, *http://www.ioes.saga-u.ac.jp/ioes-study/li/lithium/occurence.html.*

[32] "Lithium," Mineral Information Institute, http://www.mii.org/Minerals/photolith.html.

[33] Ibid.

[34] "Chile's Underground Riches," *World News Network*. To access the video on how lithium is mined in Chile, copy or type the following link into a browser window: http://wn.com/Chile's_Underground_Riches (viewed on March 22, 2011).

[35] "Lithium Market to See Huge Overcapacity by 2020-TRU Group," mineweb.com, February 8, 2011, http://www.mineweb.com/mineweb/view/mineweb/en/page72102?oid=118766&sn=Detail.

[36] Honeywell's electrolyte R&D was conducted at its Buffalo, NY facility; the electrolyte solution will be manufactured in Metropolis, IL.

[37] "LG Chem Announces $303 Million Investment to Build Volt Battery Plant in Michigan," General Motors press release, March 12, 2010, http://gm-volt.com/2010/03/12/lg-chem-announces-303-million-investment-to-build-volt-battery-plant-in-michigan/.

[38] *Energy Storage Research and Development, Annual Progress Report 2010,* U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, January 2011, p. 22.

[39] Lowe et al., "Lithium-ion Batteries for Electric Vehicles," p. 37.

[40] "Electrification of the Transportation System," sponsored by the MIT Energy Initiative, April 8, 2010, p. 4, web.mit.edu/mitei/docs/reports/electrification-transportation-system.pdf.

[41] "Cooling Fins Help Keep Chevrolet Volt Battery At Ideal Temperature," GM News Release, February 14, 2011, http://media.gm.com/content/media/us/en/news/news_detail.brand_chevrolet.html/content/Pages/news/us/en/2011/Feb/ 0214_battery.

[42] *Energy Storage Research and Development, Annual Progress Report 2010,* U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, January 2011, p. 26.

[43] "Americas: Clean Energy: Clean Storage," Goldman Sachs, June 27, 2010, p. 17.

[44] The lithium carbonate in a cell phone weighs .10 ounces; in a car, 20 pounds. "Lithium: An Energy Source in the Desert," *CBS Evening News*, September 9, 2009.

[45] "The Lithium Battery Opportunity: More Than Meets the Ion," Source: PRTM (Pittiglio Rabin Todd & McGrath), http://www.prtm.com/StrategicCategory.aspx?id=4002&langtype=1033.

[46] The discussion of Li-ion battery making is sourced from "Lithium Cell Manufacturing," BatteryEducation.com, June 11, 2010, *http://www.batteryeducation.com /2010/06/lithium.*

[47] "PRTM Analysis Finds Li-ion Battery Overcapacity Estimates Largely Unfounded, with Potential Shortfalls Looming," *Green Car Congress*, March 22, 2010, http://www.greencarcongress.com/2010/03/prtm-20100322.html.

[48] Geographic proximity of supplier facilities to the final assembly plants is generally known as "Just In Time" inventory management and manufacturing.

[49] *Energy Storage Research and Development, Annual Progress Report 2010,* U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, January 2011, p. 13.

[50] "GM's Volt and Global Lithium Reserves," ecoworld.com, March 27, 2009, http://www.ecoworld.com/technology/ gms-volt-lithium-batteries.html.

[51] The Obama Administration has stated that the $2.4 billion ARRA investment has been more than matched by private sector investments in the same facilities. "One Million Electric Vehicles by 2015," February 2011 Status Report, U.S. Department of Energy, p. 5, *http://www.energy.*

[52] "The Recovery Act: Transforming America's Transportation Sector," U.S. Department of Energy, July 14, 2010.

[53] *Energy Storage Research and Development, Annual Progress Report 2010,* U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, January 2011, p. 9.

[54] "DoE Announces $2.4 Billion for U.S. Batteries and Electric Vehicles," Press Release from U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, August 5, 2009, http://apps1.eere.energy.gov/news/ daily.cfm/hp_news_id=192.

[55] "Vice President Biden Announces Plan to Put One Million Advanced Technology Vehicles on the Road by 2015," Press Release from U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, January 26, 2011, *http://www.energy*.gov /10034.htm

[56] "Budget Highlights, Department of Energy, FY 2012 Congressional Budget Request," p. 31, http://www.cfo.doe.gov/budget/12budget/Content/FY2012Highlights.pdf.

[57] The Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976, P.L. 94-413.

[58] Gijs Mom, "The Electric Vehicle: Technology and Expectations in the Automobile Age," The Johns Hopkins University Press, 2004, p. 271.

[59] "The Congress Needs to Redirect the Federal Electric Vehicle Program," Report to the Congress by the Comptroller General, April 9, 1979, GAO Report EMD-79-6, http://archive.gao.gov/f0302/109041.pdf.

[60] Its members are GM, Ford, and Chrysler and its goal has been to foster intercompany cooperation on advanced technology vehicles, thereby reducing R&D costs, *http://www.uscar.org/guest/index.php.*

[61] http://www.uscar.org/guest/view_team.php?teams_id=12.

[62] PNGV was established by administrative action, not legislation. Several federal agencies participated in PNGV, including the Departments of Commerce, Energy, Defense and Transportation; Environmental Protection Agency (EPA); National Science Foundation, and NASA.

[63] PNGV began its work in 1994 and used vehicles of that year as its benchmark.

[64] "Review of the Research Program of the Partnership for a New Generation of Vehicles: Seventh Report," National Research Council, 2001.

[65] The FreedomCAR and Fuel Research Program is centered in the Office of Energy Efficiency and Renewable Energy (EERE) at the U.S. Department of Energy.

[66] "Review of the Research Program of the FreedomCAR and Fuel Partnership," National Research Council, 2010, p. 148.

[67] "One Million Electric Vehicles by 2015: February 2011 Status Report," U.S. Department of Energy, p. 2, http://www.energy.gov/news/documents/1_Million_Electric_Vehicle_Report_Final.pdf.

[68] In 2010, 11.6 million light vehicles were sold in the United States; it is estimated that 12.9 million vehicles will be sold in 2011. "U.S. Car and Light Truck Sales, 2010," *Automotive News*, January 4, 2011 and "North America Forecast and Analysis," Global Insight, January 31, 2011.

[69] "Obama Administration Says Electric-Car Goal Achievable, But Relies on Unconfirmed Data," *Washington Post*, February 7, 2011, http://www.washingtonpost.com/wp-dyn/content/article/2011/02/07/AR2011020705616.html.

[70] The report is based on the findings of a Transportation Electrification Panel held in spring 2010. The panel comprised experts from several universities, Argonne National Laboratory, Ford Motor Company, and the Center for Automotive Research; other contributors were from General Motors Company, Nissan Motor Company, EnerDel and the Electric Drive Transportation Association. "Plug-in Electric Vehicles: A Practical Plan for Progress, The report of an Expert Panel," School of Public and Environmental Affairs, Indiana University, February 2011, p. 27, http://www.indiana.edu/~spea/pubs/TEP_combined.pdf.

[71] The previous section of this report summarizes the President's budget proposals for new incentives for electric battery development. "One Million Electric Vehicles by 2015: February 2011 Status Report," U.S. Department of Energy, p. 2.

[72] The cost of Li-ion batteries in the Chevrolet Volt and Nissan Leaf have not been disclosed. Marcy Lowe et al., "Lithium-ion Batteries for Electric Vehicles," p. 42. This report breaks down the cost of a $16,000 Li-ion battery: 29% for materials, 16% for Li-ion cell manufacturing labor costs, 22% for electronics and mechanical components, 30% for gross profit, including research and development costs and the remainder for other manufacturing and warranty costs. The Volt retails for $40,280 and the Leaf for $33,720. Sources: http://www.chevrolet.com/volt and http://www.nissanusa.com/leaf-electric-car.

[73] "Plug-in Electric Vehicles: A Practical Plan for Progress, The report of an Expert Panel," School of Public and Environmental Affairs, Indiana University, February 2011, p. 36.

[74] "Roush Starts Projection of Electric Car Chargers," *Bloomberg BusinessWeek*, February 11, 2011, http://www.businessweek.com/ap/financialnews/D9LAP3UG2.htm.

[75] Regenerative braking systems are used on other hybrids, such as the Toyota Prius and Tesla Roadster, and on electric bicycles and even trolley cars. "How Regenerative Braking Works," HowStuffWorks.com, http://auto.howstuffworks.com/auto-parts/brakes/brake-types/regenerative-braking.htm.

[76] "Gas Mileage: 40 MPG is the New 30," *CBSMoneywatch.com*, February 7, 2011. The Volt retails for $40,280; the Leaf for $33,720.

[77] Marcy Lowe et al., “Lithium-ion Batteries for Electric Vehicles,” p. 37.

[78] “Germany Frets About its Car Industry,” *Wall Street Journal*, February 28, 2011.

[79] “Germany Frets About its Car Industry,” *Wall Street Journal*, February 28, 2011.

[80] Ibid.

[81] The Nissan Leaf is being marketed globally and has reportedly sold additional vehicles in other countries. Sales data are from “U.S. Light Vehicle Sales by Nameplate, February and 2 Months 2011,” *Automotive News*, March 1, 2011.

[82] Marcy Lowe et al., “Lithium-ion Batteries for Electric Vehicles,” p. 69.

[83] “Plug-in Electric Vehicles: A Practical Plan for Progress, The report of an Expert Panel,” School of Public and Environmental Affairs, Indiana University, February 2011, p. 66.

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Chapter 2

ONE MILLION ELECTRIC VEHICLES BY 2015

U.S. Department of Energy

EXECUTIVE SUMMARY

President Obama's goal of putting one million electric vehicles on the road by 2015 represents a key milestone toward dramatically reducing dependence on oil and ensuring that America leads in the growing electric vehicle manufacturing industry. Although the goal is ambitious, key steps already taken and further steps proposed indicate the goal is achievable. Indeed, leading vehicle manufacturers already have plans for cumulative U.S. production capacity of more than 1.2 million electric vehicles by 2015, according to public announcements and news reports. While it appears that the goal is within reach in terms of production capacity, initial costs and lack of familiarity with the technology could be barriers. For that reason, President Obama has proposed steps to accelerate America's leadership in electric vehicle deployment, including improvements to existing consumer tax credits, programs to help cities prepare for growing demand for electric vehicles and strong support for research and development.

INTRODUCTION

In his 2011 State of the Union address, President Obama called for putting one million electric vehicles on the road by 2015 – affirming and highlighting a goal aimed at building U.S. leadership in technologies that reduce our dependence on oil.[1] Electric vehicles ("EVs") – a term that includes plug-in hybrids, extended range electric vehicles and all-electric vehicles -- represent a key pathway for reducing petroleum dependence, enhancing environmental stewardship and promoting transportation sustainability, while creating high quality jobs and economic growth. To achieve these benefits and reach the goal, President Obama has proposed a new effort that supports advanced technology vehicle adoption through improvements to tax credits in current law, investments in R&D and competitive programs to encourage communities to invest in infrastructure supporting these vehicles.

> *"With more research and incentives, we can break our dependence on oil with biofuels, and become the first country to have a million electric vehicles on the road by 2015"*
>
> \- President Barack Obama, 2011 State of the Union

While several high profile vehicle market introductions such as the Chevrolet Volt and the Nissan Leaf have been initiated, questions remain regarding the potential to reach the 2015 goal. Production capacity must be established, and technology, vehicle cost and infrastructure barriers must be addressed to achieve large-scale market introduction. This report provides a progress update toward achieving the goal:

- The status of vehicle sales and future production volume estimates
- Current federal government policies, investments, research and development, and demonstration efforts supporting the deployment of EVs
- EV consumer demand

This is an exceedingly dynamic and competitive field. Major announcements by companies and governments worldwide are made on a frequent basis. The plans of global companies and the policy initiatives of governments will surely change and shape the development of technology and markets during the next five years.

WHERE WE ARE TODAY

In 2010, the U.S. economy continued recovery from recession. As part of that recovery, sales of U.S. light-duty vehicles rebounded to approximately 12 million in 2010 from less than 10 million in 2009. Historically, U.S. sales of new light duty passenger vehicles ranged from 15-16 million per year from 2005-2008.[2] Conventional hybrid electric vehicles (HEVs) have been on sale in the U.S. for over ten years, and today sales have grown to almost three percent of total light-duty vehicles. Over 1.6 million HEVs have been sold over the past six years.[3] To reach the one million vehicle goal, EVs will need to average just under 1.7 percent of sales through 2015 (assuming sales of 12 million light-duty vehicles per year).

With increases in the Corporate Average Fuel Economy (CAFE) standards, vehicle manufacturers are required to increase fuel economy through 2016, with further increases beyond 2016 under consideration. On March 30, 2009, the National Highway Traffic Safety Administration (NHTSA) published the final rule raising CAFE standards for both cars and light trucks. These new standards will encourage the expanded market entry of electric drive technologies.

Market for Electric Drive Vehicles Expected to Increase

Over the past few years, interest in EVs in the U.S. auto industry has surged, with manufacturers beginning to introduce new generations of EVs. For example, in 2010 General Motors introduced the Chevrolet Volt extended range electric vehicle into the U.S. market. The Volt can travel up to 40 miles using power from its lithium-ion battery pack. After that, the Volt can travel up to 375 miles in extended range using its internal combustion engine electric generator. GM has announced plans to build 15,000 Chevy Volts in 2011 and 45,000 in 2012. Based on news reports, the company is working on plans to increase its production target for 2012 to 120,000. (See Table references.) In late 2010, Nissan introduced the Leaf, a 100-mile range all-electric vehicle that incorporates an advanced lithium-ion battery as its sole power source.

The 2011 Chevrolet Volt.

The 2011 Nissan Leaf.

The production capacity of EV models announced to enter the U.S. market through 2015 should be sufficient to achieve the goal of one million EVs by 2015. The table below shows EVs expected to enter the U.S. commercial market over the next few years, including the production capacity by year, based on manufacturer announcements and media reports. Major auto manufacturers such as Chrysler, BYD, Coda, Honda, Mitsubishi, Hyundai, Toyota, Volkswagen and Volvo are not included in this table, but have announced or are expected to introduce EVs in this time period. Because the U.S. is a major market for these automakers, it is likely that additional production capacity of several hundred thousand EVs is not accounted for in this table.

Estimated U.S. Supply of Electric Vehicles from 2011 through 2015.

Manufacturer and Model	2011	2012	2013	2014	2015	Total
Fisker Karma PHEV	1,000	5,000	10,000	10,000	10,000	36,000
Fisker Nina PHEV		5,000	40,000	75,000	75,000	195,000
Ford Focus EV		10,000	20,000	20,000	20,000	70,000
Ford Transit Connect EV	400	800	1,000	1,000	1,000	4,200
GM Chevrolet Volt	15,000	120,000	120,000	120,000	120,000	505,000
Navistar eStar EV (truck)	200	800	1,000	1,000	1,000	4,000

Manufacturer and Model	**2011**	**2012**	**2013**	**2014**	**2015**	**Total**
Nissan LEAF EV	25,000	25,000	50,000	100,000	100,000	300,000
Smith Electric Vehicles Newton EV (truck)	1,000	1,000	1,000	1,000	1,000	5,000
Tesla Motors Model S EV		5,000	10,000	20,000	20,000	55,000
Tesla Motors Roadster EV	1,000					1,000
Think City EV	2,000	5,000	10,000	20,000	20,000	57,000
Cumulative Total						1,222,200

Note: The above numbers have been taken from announced production figures and media reports. In some cases more conservative estimates have been used due to: delays that have occurred since announced production levels, ramp rates to reach full production, consideration of the size of the market segment for that vehicle, and possible exportation of vehicles manufactured in the U.S. See the reference table for citations.

POLICY

In recent years there have been a number of federal and state policy initiatives to encourage the introduction and sales of EVs. Industry can achieve its planned production with the support of policies that encourage investment in manufacturing facilities, enable technology demonstration and deployment and provide incentives to promote adoption and drive consumer demand.

Manufacturing Investments

Through the Recovery Act, the United States made an unprecedented investment to build our domestic manufacturing capacity and secure our position as a global leader in advanced lithium-ion battery technology. This investment includes:

- $2.4 billion in loans to three of the world’s first electric vehicle factories in Tennessee, Delaware, and California.
- $2 billion in grants to support 30 factories that produce batteries, motors, and other EV components. Companies are matching the

funding dollar for dollar, doubling the impact of taxpayer investments. These grants are enabling companies to build the capacity to produce 50,000 EV batteries annually by the end of 2011 and 500,000 EV batteries annually by December 2014.

Deployment, Demonstration, and Outreach

Recovery Act funds are also supporting the largest-ever coordinated demonstration of EVs, including nearly 13,000 vehicles and more than 22,000 electric charging points in more than 20 cities across the country. Companies are matching this $400 million public investment dollar for dollar. This effort will provide important and detailed real-world operational data on vehicle usage, time-of-use and charging patterns, and potential impacts on our nation's electrical grid. The demonstrations will document lessons learned that help streamline infrastructure permitting processes and make data available that can alleviate consumer uncertainty and help transition EVs from clusters of early adopters to national, mainstream use. Coordinated with this large-scale demonstration are programs to educate code officials, first responders, technicians, and engineers, who are critical components of the human infrastructure needed for a successful transition to electric-drive transportation, both in terms of consumer acceptance and public safety.

The Department of Energy is also working with local leaders in their efforts to encourage EV adoption and drive consumer demand. Through a new competitive program, seed funding will help communities across the country with regulatory streamlining, infrastructure investments, vehicle fleet conversions, deployment of EV incentives, partnerships with major employers/retailers, and workforce training. The FY12 budget request seeks to expand this initiative so that up to 30 communities could receive grants of up to $10 million to help catalyze EV deployment (see text box on page 6).[4]

Incentives

Tax incentives and other measures have been proven effective in providing the additional boost needed for mainstream consumers to choose EVs. The Recovery Act established tax credits for purchasing electric vehicles ($2,500 - $7,500 per vehicle, depending on the battery capacity) and conversion kits to retrofit conventionally powered vehicles with electric vehicle capability ($4,000 per vehicle, maximum). The President has also proposed transforming the existing $7,500 EV tax credit into a more accessible and even more attractive rebate at the dealership.[5] In addition, nearly 40 U.S. states and the District of Columbia have adopted other measures promoting electric-drive vehicle usage, including high occupancy vehicle (HOV) privileges and waived emissions inspections, as well as tax credits/rebates and preferred purchase programs.[6]

NEW INITIATIVES TO SUPPORT ADVANCED TECHNOLOGY VEHICLES

President Obama is proposing three steps to address consumer demand and position the United States as a global leader in manufacturing and deploying next-generation vehicle technologies:

- **Make electric vehicles more affordable with a rebate up to $7,500:** The President is proposing to transform the existing $7,500 tax credit for electric vehicles into a rebate that will be available to all consumers immediately at the point of sale.
- **Advance innovative technologies through new R&D investments:** Building on Recovery Act investments, the President's Budget proposes enhanced R&D investments in electric drive, batteries, and energy storage technologies.
- **Reward communities that invest in electric vehicle infrastructure through competitive grants:** To provide an incentive for communities to invest in EV infrastructure and remove regulatory barriers, the President is proposing a new initiative that will provide grants to up to 30 communities that are prioritizing advanced technology vehicle deployment.

Source: http://www.whitehouse.gov/the-press-office/2011/01/26/vice-president

ADVANCING TECHNOLOGIES THROUGH R&D

The President has announced that the FY 2012 Budget will include enhanced R&D investments in battery and other electric drive technologies.[7] Investments will support R&D initiatives through DOE's Vehicle Technologies Program, as well as a new Energy Innovation Hub devoted to developing better batteries and energy storage capacity to support electric vehicles and other technologies. This focus on continued innovation complements ongoing R&D to support the development of critical technologies needed for the widespread introduction of electric drive vehicles. These efforts include battery development, power electronics and electric motors, and electric drive vehicle systems.

A123 Systems Battery Module.

Battery technology today is greatly different from that of the 1990s. The General Motors EV-1 had a range of 80 to 140 miles, but initially used lead-acid batteries having limited energy density, which resulted in a two-passenger vehicle, relatively short battery life, and a long recharging time. By contrast, today's lithium-ion battery technology allows the Leaf, Volt, and other EVs to be 4- or 5-passenger vehicles, with an extended warranty on battery life, and much faster charging times. The Volt's lithium-ion battery technology is over 70 percent lighter than the EV-1's original lead-acid battery technology.

Vehicle manufacturers currently employ lithium-ion batteries with excess capacity to ensure the batteries meet a ten-year battery life target. As greater confidence in battery life under real-world driving conditions develops, the amount of excess capacity installed is expected to decrease, and thus cost should decrease as well. GM recently announced that the Chevrolet Volt battery will now be operated using more than 65 percent of total capacity, instead of 50 percent, demonstrating continued improvement in today's lithium-ion batteries.[8] Next-generation lithium-ion batteries are likely to employ advanced electrodes such as silicon-based nanostructured anodes (instead of graphite), and high-capacity manganese-based cathodes, resulting in a significant increase in energy density and reduction in cost. New technologies continue to move from DOE laboratories to market– most recently Argonne National Laboratory has licensed advanced cathode technology to General Motors and battery suppliers LG Chem and Envia.

These companies will now have the opportunity to build on DOE’s technology innovation with further improvements and specific market applications.

Recovery Act investments will help cut battery costs. DOE and U.S. industry have invested over $3 billion in battery manufacturing facilities using Recovery Act and matching funds. Increasing the production output of a battery plant from 10,000 units/year to 100,000 units/year can directly reduce battery costs by 30-40 percent.[9] DOE’s established cost target of $300/kWh by 2015 is an aggressive but achievable goal for lithium-ion batteries. Electric vehicle battery prices are expected to drop due to increased manufacturing know-how and economies-of-scale, learning curve improvements, lower-cost battery materials, and technical advancements in battery design.

DOE supports a broad portfolio of electric drive vehicle battery R&D that spans basic research to applied development. The Office of Science supports fundamental basic energy research on enabling materials through the Energy Frontiers Research Centers. The Applied Research Projects Agency - Energy (ARPA-E) conducts transformational research on revolutionary, “game-changing” energy storage technology. And the Office of Energy Efficiency and Renewable Energy (EERE) battery R&D is focused on applied development and demonstration of advanced batteries to enable a large market penetration of electric drive vehicles.

CONSUMER DEMAND

While leading manufacturers already have plans for cumulative U.S. production capacity of more than one million electric vehicles by 2015, according to public announcements and news reports, production will only reach levels supported by consumer demand. What issues will influence purchasing decisions?

Fleet buyers tend to make vehicle purchasing decisions based on the total cost of vehicle ownership; retail vehicle consumers tend to focus on initial price. The Boston Consulting Group report on “Batteries for Electric Vehicles” concluded that with current incentives and oil prices in the United States, EV purchasers will reach lower total ownership costs within 3 to 5 years of operation.[10] These increasingly favorable economics for EVs aren’t going unnoticed by fleet buyers. General Electric announced that they will purchase 25,000 EV by 2015[11] – a strong indication that as EV total cost of ownership falls below that of conventional vehicles, fleet purchasers will respond positively.

With the exception of a small segment of the new car buyer population, automobile consumers tend to be risk-averse, preferring well-proven technology. With automotive purchases generally the second largest financial purchase most families make, behind only housing, cost is considered carefully. And while automobile consumers do consider fuel consumption, they tend to discount future fuel savings. Studies have shown that consumers tend to assume that current fuel prices are good estimates of future prices.[12] Thus purchasers during periods of high fuel prices value fuel efficiency more than purchasers during periods of low fuel prices.

While availability of the current $7,500 tax credit is attractive to consumers, the President's proposal to convert this credit to benefit the consumer at the point-of-sale will likely make the incentive even more attractive since consumers will not have to wait until the end of the year to receive the credit.[13]

Although consumers have proven to be highly sensitive to initial price, they are also willing to pay premiums for vehicle options or attributes that resonate with them. EVs have unique attributes which may appeal to consumers. Exceptionally quiet operation, high torque (good acceleration), and low lifetime operating costs are examples of attributes that will attract consumers. Other features may also prove attractive to consumers, such as avoiding the gasoline refueling experience. In addition, car purchasing decisions are influenced by style and statements of personal identity; the powertrain configurations of EVs will provide styling options not available to conventionally powered vehicles.

Fuel price matters when consumers make automobile purchasing decisions. If oil prices increase, or expectation of further oil price increases becomes prevalent,[14] interest in EVs will likely increase as well.

There is clearly substantial consumer interest in electric vehicles, as demonstrated by the larger-than-anticipated pre-orders for the Nissan Leaf and the Chevrolet Volt. Whether this interest translates into sales beyond the initial "early adopter" market will depend on initial consumer experience with these early vehicles, and on how that experience is communicated and perceived by the rest of the car buying public. Uncertainties about EVs – including their resale value, range and availability of convenient charging facilities -- may impose sales barriers.

As noted earlier, there is considerable work underway to develop data on performance and reliability of EVs, and to communicate that information to the public. The performance and cost effectiveness of the early EVs in the market will be a major but unknowable factor in how many EVs are on the road by 2015. The cumulative impacts of the various policy initiatives, the experience of the early purchasers of electric-drive vehicles and future oil prices will all play a role in determining future consumer demand.

SUMMARY

In his 2011 State of the Union address, President Obama called for putting one million electric vehicles on the road by 2015 – affirming and highlighting a goal aimed at building U.S. leadership in technologies that reduce our dependence on oil. This goal represents a key milestone in transforming our national vehicle fleet, a transformation that will deliver significant benefits for the American people, including:

- Dramatically reducing petroleum dependence and improving transportation sustainability;
- Improved environmental stewardship;
- Job creation and economic growth.

Government policies are critical enablers which influence the rate that advanced vehicles are adopted on a large scale. In addition to existing policies, the Administration's new three-part plan supports electric vehicle manufacturing and adoption through improvements to tax credits in current law, investments in R&D, and a new competitive program to encourage communities to invest in electric vehicle infrastructure. These policies will help attain the 2015 goal.

Reaching the goal is not likely to be constrained by production capacity. Major vehicle manufacturers have announced (or been the subject of media reports) that indicate a cumulative electric drive vehicle manufacturing capacity of over 1.2 million vehicles through 2015.

Strong incentives, research and development, and assistance in establishing manufacturing and infrastructure is underway or planned. These activities directly support consumer demand of these technologies, and mitigate some of the uncertainty associated with the large-scale adoption of electric drive vehicles.

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Chapter 3

COMPARATIVE COSTS OF FLEXIBLE PACKAGE CELLS AND RIGID CELLS FOR LITHIUM-ION HYBRID ELECTRIC VEHICLE BATTERIES

Argonne National Laboratory
and Chemical Engineering Division

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GLOSSARY OF TERMS

Argonne	Argonne National Laboratory
ASI	Area specific impedance (ohm-cm^2)
Double seaming	Mechanical closure for containers that performs a crimp by double folding the container and cover and is commonly used on food “cans.”
Flex cell	Flexible multi-laminate containment package
LBW	Laser beam welding
Rigid cell	Metal cell container
TIG welding	Welding procedure performed in an inert gas atmosphere using a tungsten electrode

EXECUTIVE SUMMARY

We conducted a design study to compare the manufacturing costs at a level of 100,000 hybrid vehicle batteries per year for flexible package (Flex) cells and for rigid aluminum container (Rigid) cells. Initially, the Rigid cells were considered to have welded closures and to be deep-drawn containers of about the same shape as the Flex cells. As the study progressed, the method of fabricating and sealing the Rigid cells was expanded to include lower cost options including double seaming and other mechanically fastened closures with polymer sealants. Both types of batteries were designed with positive electrodes containing $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ and graphite negative electrodes. The use of a different combination of lithium-ion electrodes would have little effect on the difference in costs for the two types of cells. We found that 20-Ah cells could be designed with excellent performance and heat rejection capabilities for either type of cell. Many parts in the design of the Flex cells are identical or nearly identical to those of the Rigid Cell, so for these features there would be no difference in the cost of manufacturing the two types of batteries. We judged the performance, size and weight of the batteries to be sufficiently similar that the batteries would have the same value for their application.

Some of the design features of the Flex cells were markedly different than those of the deep-drawn and welded Rigid cells and would result in significant cost savings. Fabrication and processing steps for which the Flex cells appear to have a cost advantage over these Rigid cells are (1) container fabrication and sealing, (2) terminal fabrication and sealing, and (3) intercell connections. The costs of providing cooling channels adjacent to the cells and for module and battery hardware appear to favor Rigid cell batteries slightly. Overall, Flex cell batteries appear to have an advantage of about \$1.20-\$3.70 per cell for a 25-kW Battery of 20 cells or about \$24 to \$74 per battery.

Container experts assisted with this study, including a paid consultant and personnel at container manufacturing companies. Some of the companies are considering entering the business of manufacturing containers for hybrid vehicle battery manufacturers. For this reason they provided valuable guidance on overall approaches to reducing the costs of the cell containers. They have retained the description of some specific designs and procedures for future possible work with battery manufacturers, with whom they are now in contact.

Through the guidance of these experts, we determined that a new type of container could be manufactured that would have the best features of performance and low cost of both the Rigid and Flex containers. For instance, the aluminum layer in a tri-layer sheet can be sufficiently thick to form a rigid container that can be fabricated in two halves, much like a Flex container, and mechanically joined at the edges for strength. In addition to the mechanical joint, this container can be sealed at the edges, much like a Flex container, by means of an inner polymer liner that can be heat-sealed or ultrasonically welded. The terminals can be flat strips of metal sealed into the top of the container as part of the edge sealing of the container, as for the Flex cell. Ridges can be stamped into one side of the container to provide cooling channels and the exterior layer of the container stock can be coated with a thin, electrically insulating, polymer layer. We expect this type of container will provide excellent sealing and durability and be less expensive than either the Flex or the Rigid container, which the study initially considered.

A major cost for the original Rigid container is the welding required for sealing the container. However, the welding of the current collector tabs to the terminal piece may be even more complex and costly than welding the container. It is important, therefore, to develop an inexpensive procedure for attachment of the foils to the terminal pieces. A lower-cost procedure, such as ultrasonic welding or mechanical clipping, might replace laser welding of the foils to the terminal pieces.

A conclusion from our discussions with the container experts is that the manufacturing rate required for the containers for hybrid vehicle batteries is fairly low, and thus favors procedures requiring low tooling costs and little development effort. These conditions favor flexible packaging, heat sealing, shallow stamping, double seaming and ultrasonic welding. It works against deep drawing and untested procedures for welding and joining.

1. INTRODUCTION

A previous report [1] described the concept of replacing the rigid container used for prismatic lithium-ion cells with a flexible multi-laminate containment package of a type commonly used in the food packaging industry. That report described testing procedures and preliminary results that were used to set the test criteria and target values that are required to achieve a 15-year life for the flexible packaging container for the battery application.

The purpose of this study was to compare the costs of producing a hybrid vehicle battery of flexible package (Flex) cells and a similar battery of cells with deep-drawn aluminum containers (Rigid cells). A complicating factor is that neither Flex cell nor Rigid cell batteries have been designed in sufficient detail for accurate cost estimates, which would require quotes from processing equipment manufacturers and the determination of manufacturing space and personnel requirements. The complexity of the task was reduced by designing similar Flex and Rigid cells so that it was only necessary to estimate the costs of those cell and battery characteristics that differed significantly to obtain an overall estimate of the difference in the costs of manufacturing the two types of batteries.

The design effort included both the sketching of cell and battery configurations, which are described below, and the calculating of performances of 25-kW hybrid vehicle batteries, which is described in detail in Appendix A, Design Modeling. Both types of batteries were designed with positive electrodes containing $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ and graphite negative electrodes. The selection of other lithium-ion electrode materials would not be expected to affect the difference in costs of the two types of batteries. Design and calculation of the performance of the entire batteries was necessary because the design of the cells could impact the design and cost of module and battery hardware.

The overall strategy for saving cost with flexible packaging versus the use of deep-drawn aluminum containers is the following:

- Reduce the cost of the container fabrication.
- Seal the terminals and container in one quick step with a low-temperature (2 15°C) sealing operation.

- Substitute a low-cost method for the laser welding of current collectors to terminal pieces.
- Simplify the terminals by the use of flat metal strips.
- Simplify the interconnection of cells.

The designs of the two types of cells reflected the above strategy, but where applicable, advances proposed for the Flex cell were also applied to the Rigid cell, such as attaching the current collector foils to the terminal piece by a low-temperature, low-cost method instead of by laser welding.

One approach to reducing the overall cost of the battery is to use a small number of moderately large cells in the battery and thus reduce the costs of cell and battery hardware, monitoring devices, and the state-of-charge equalization controller. After preliminary calculations we found that cells of 20-Ah capacity could be designed with a thin cross-section (about 14 mm thick) and this cell size, which requires only 20 cells for a 25-kW battery, was selected as the standard for this study. Sketches of the Flex cells and Rigid cells of this study are shown in Figures 1 and 2, respectively.

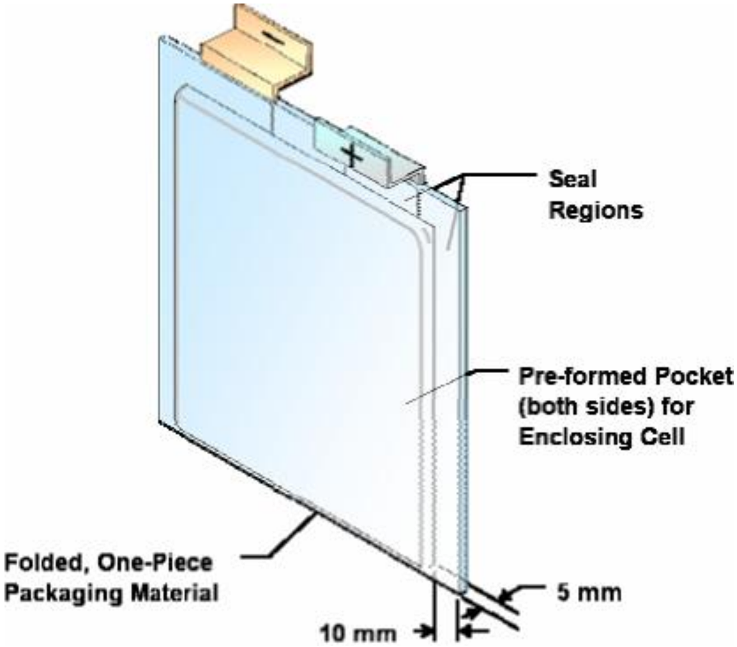


Figure 1. Lithium-Ion Flexible Packaging Cell (Flex Cell).

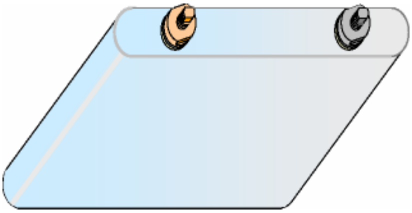


Figure 2. Lithium-Ion Cell in Deep-Drawn Aluminum Container (Rigid Cell).

Good temperature control for the lithium-ion battery is important for long life, safety, and power after startup in very cold weather. Provision must be made for coolant passages between cells and this is a special problem for the Flex cells, for which the container material is not sufficiently rigid and creep-resistant to be configured for coolant passages. A dielectric fluid, such as a transformer fluid, is a better coolant than air, especially during a cell malfunction when the rate of thermal energy generated within the cell may be many times the normal rate. The use of a dielectric coolant has an added advantage in that it serves to hinder the transfer of moisture into the cell through the polymer seals of the terminals and container closures and, likewise, to hinder diffusion of solvent vapor out of the cell. In Appendix B, Thermal Management, thermal management issues that are only indirectly related to the relative costs of the two types of cells are discussed and the advantages for a dielectric coolant are considered. In that section we present our conclusions that, on the basis of its improved thermal performance alone, a dielectric coolant could be justified versus air coolant for use in both types of batteries.

The attractiveness of lithium-ion batteries for the hybrid vehicle application is based upon very high power capability, high specific energy, moderate electrode costs, and prospects for long life. Potential disadvantages, which must be met at low cost for success, are the need for (1) electronically controlled state of charge equalization for each cell and (2) avoidance of a temperature runaway resulting from excessive heat generation caused by cell or control system malfunctions. These require careful monitoring of voltage and temperature at each cell for control purposes and for early warnings of cell malfunctions. Pressure sensors for each cell can also be provided as discussed below. More detail on these subjects is presented in Appendix C, Safety and Monitoring.

During this cost study, we consulted container experts to assist us in assessing costs and to guide us in selecting designs for study. Stephen W. Cornell, a paid Argonne consultant who previously directed research and development for major container manufacturers, assisted us in selecting designs for study and in arranging visits with personnel from several firms involved in container development and manufacturing. These personnel included, Len Jenkins, Vice President, and Michael R. Gredlics of Technology Development, Crown Packaging Technology, Alsip, Illinois; William J. Reimann, President of Flex-Pak, Inc., Batavia, Illinois; and James Rinehart, Co-owner of Integrated Solutions, Waukegan, Illinois.

The personnel from Crown directed our attention to a rigid container design that combines the main performance and cost advantages of both the Rigid and Flex designs. An approximate sketch of this design is shown in Figure 3. Because this new approach came rather late in the study, the costs of the Rigid and Flex cells are discussed without regard to this design in the sections below and then the new approach is discussed separately in Section 4, Rigid Container with Polymer-Sealed Terminals.

2. COST COMPARISON

2.1. Cost of Fabrication of Cell Windings

Both the Flex and the Rigid container designs employ a flat-wound cell configuration, which is fabricated by wrapping bicell sheets around a flat core. The bicell sheets consist of negative electrode coatings on both sides of a copper current collector foil, a separator sheet, positive coatings on both sides of an aluminum foil, and a second separator sheet. The copper foil extends beyond the coatings and the separator sheets at the top of the cell and the aluminum foil extends beyond the coatings and separator sheets at the bottom of the cell to facilitate attachment of the current collector sheets to the terminal pieces or their extensions.

The cores about which the windings are wrapped are polymer plates with recesses to receive the terminal pieces that are fastened to them (Figures 4 and 5). Even though the terminal pieces are different for the two types of cells, there is very little difference in the handling of the core assemblies during the cell winding operation. In both cases the terminal pieces would probably be in place during winding, although they might be slipped into place after the winding for either cell type, if that would facilitate the winding operation.

The Rigid cell has only slightly more (1.4%) cell area than the Flex cell to balance the higher resistance in the Rigid cell terminals and connections (Appendix A, Design Modeling*)*. These nearly identical cell areas result in insignificant differences in the dimensions of the cell windings. The number of cell wraps is largely responsible for determining the thickness of the cells. The Flex cell thickness is limited by the maximum thickness that can be enclosed in an economical flexible package and the Rigid container must be thick enough to accommodate a cylindrical feedthrough. A cell thickness of 12 to 14 mm is near optimum for both designs and was selected as a target.

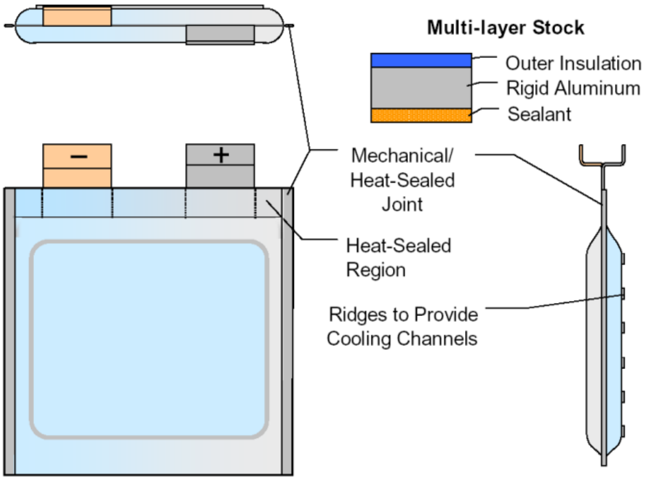


Figure 3. Cell with Rigid Container and Heat-Sealed Terminals.

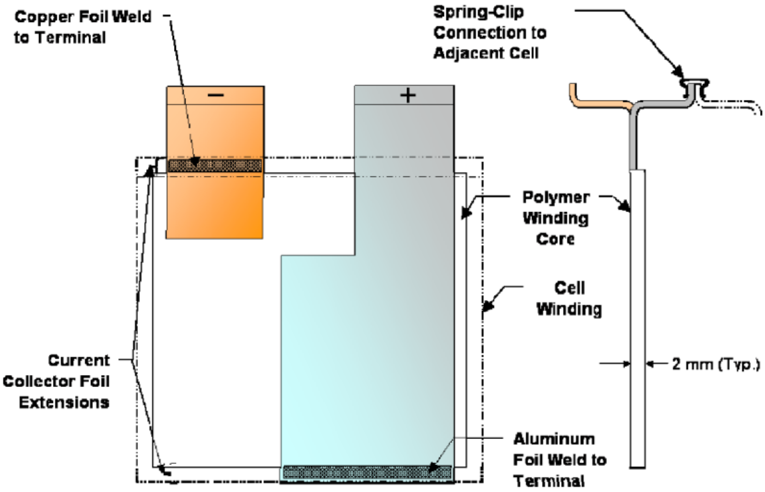


Figure 4. Terminal/Core Assembly for Flexible Package Cell.

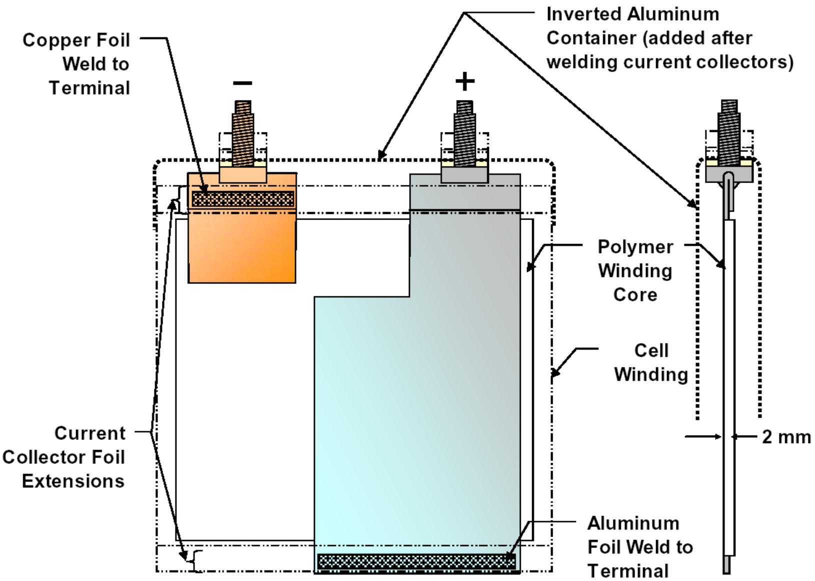


Figure 5. Terminal/Core Assembly for Rigid Aluminum Container.

With 23 windings around the cell core, both types of cells are about 14 mm thick and, therefore, 23 was selected as the number of windings for the baseline cells of both types. The thin cross-section of these cells results in excellent heat rejection characteristics.

Since the windings are so similar, no cost difference for the winding materials or fabrication of the windings is expected for the two methods of cell packaging under consideration. This resulted in great simplification of the cost study because the cost of the winding materials and fabrication are difficult to assess without detailed designs, detailed fabrication procedures, and well established manufacturing equipment.

2.2. Cost of Attachment of Electrodes to Terminals

One of the low-cost packaging features we sought is the avoidance of high-temperature welding of the current collector foils to the terminal pieces. Because of the sensitivity of the electrodes and separators to high temperature, the high-temperature welding technique of choice has been laser beam welding (LBW) for which high temperature can be confined to a small region. In welding single tabs or larger pieces LBW is effective, but work at Mine Safety

Appliances Company on 50-Ah lithium-ion cells, found that the simultaneous welding of many foils of aluminum to a terminal piece resulted in porosity and voids in the welds [2]. A promising cold welding technique for attachment of electrode foils to the terminals is ultrasonic welding. In the Mine Safety Appliances study, ultrasonic welding of 10 foil tabs to a single feeder tab was successful, resulting in connections with very low resistance [2]. Welding of as many as 23 foils on each side of the terminal piece as required by the designs for the 20-Ah baseline cells of this study is believed to be feasible with a moderate development effort and, potentially, to have low cost in production.

Another approach that should be considered is attachment using specially designed spring clips to attach both the positive current collectors at the bottom of the cell and the negative current collector foils at the top of the cells to their respective terminal pieces (Figure 6). This approach would require experimentation to determine if insulating layers build up between the attached metal parts under cell operating compositions and potentials, which would cause increasing cell resistance. If it can be shown that connections of this type can be made with low resistances over a long life, this method of attachment could be rapid and result in low costs for mass production.

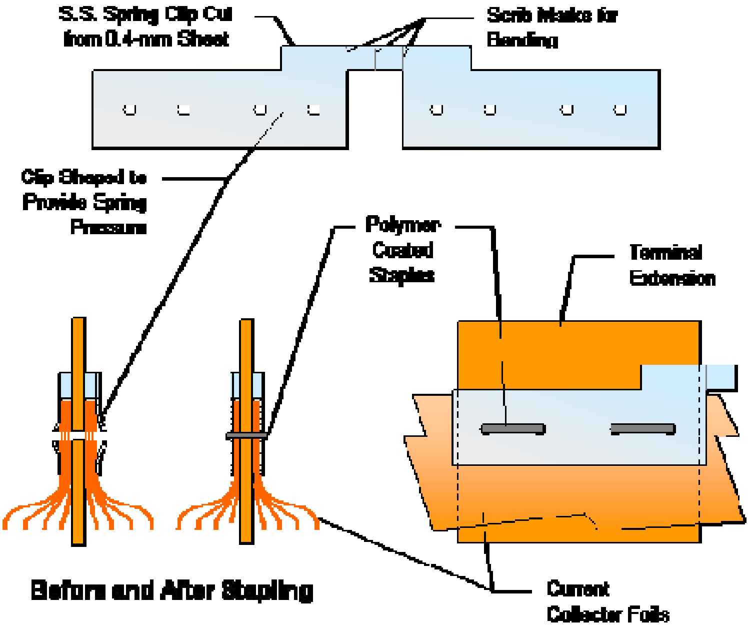


Figure 6. Connection of Current Collector Foils to Flat Terminals Using Stapled Spring Clips.

The designs for the winding assemblies for the flexible packaging cells and the rigid container cells are very similar. Whichever technique for attachment of the current collector foils to the terminals is employed for one packaging approach will work equally well for the other. As a result, no cost difference for attaching the current collector foils to the terminal pieces is expected for the two packaging methods. However, the success in finding an excellent low-cost method of current collector attachment is vital for the overall success in developing a low-cost lithium-ion battery.

2.3. Cost of Container Fabrication and Sealing

The greatest differences between the two packaging approaches are in the fabrication and the sealing of the packages themselves (Figures 1 and 2). The flexible package material is made in sheets that can be used for containers of any desired dimensions and even for batteries for more than one application. The usefulness of the same flexible packaging for cells of different sizes is especially important at low production rates and when the cell size has not been standardized. Pressing a pocket into both sides of the flexible packaging sheet that is to enclose the cell may be advantageous for accommodating the thickness necessary for the cell winding. This pocket formation has already been done without difficulty in test cells made for Argonne by Sumitomo Electric Industries, LTD [1]. The tooling required for forming the pocket to receive the winding is simple and inexpensive.

A concern that must be addressed for the flexible packaging is the effectiveness of measures to prevent diffusion of moisture into the package and diffusion of electrolyte solvent out of the package. Two layers of aluminum are effective in blocking diffusion through the side walls, but diffusion through the seal area is equally important. Calculations based on published values of the permeability coefficients through the polymer sealant materials [3] indicate that, with care in the design, the seals of both types of cells will sufficiently block the diffusion of water and organic solvents to achieve 15-year life. The use of a hermetically sealed battery pack, such as can be done if a silicone transformer coolant is used as is proposed for both cell packaging approaches, would serve as an additional barrier to hinder the ingress of water and air.

The rigid aluminum container requires tooling for fabrication that is unique for the particular dimensions of the container. The cost of this tooling depends on the container design. The most expensive design is a deep-drawn container (Figure 2). It is apparent that at very high production rates of a standard size, for instance 12-oz beverage containers, deep-drawn aluminum containers can be quite inexpensive. For moderate production rates of 2,000,000/yr (100,000 20-cell batteries/yr), the market for the container supplier would be $2,000,000/yr at $1.00 per cell container. At that moderate production rate, the tooling development, setup and retooling costs might be a significant fraction of the total revenue to the supplier. Also, even slight changes in cell size would result in a loss of the inventory of finished containers and the need to retool. A starting rough estimate cost of $1.00/cell to the battery manufacturer was deemed plausible for deep-drawn aluminum containers and matching covers.

A thin cell design, while advantageous for cooling, would present a difficulty for the Rigid cell in welding the cover to the container near the terminals. We propose that the container be slipped on from above the winding and that the closure be made at the bottom of the cell (Figures 2 and 5). This approach requires holes in the “bottom” of the inverted container to receive the terminals.

An alternative to welding for closing the container is crimping by double seaming, as is done for food “cans.” Double seaming is an inexpensive method of closing a container and makes it possible to circumvent deep drawing. A three-piece container can be constructed by double seaming both the top and the bottom of the container that has a body constructed by bending and welding a flat sheet (Figure 7), which is similar to the construction of a container for machine oil. A two-piece container can be constructed from a shallow-drawn container with a double-seamed closure on the side of the container (Figure 8) similar to the construction of a sardine can. The three-piece container is more commonly made from steel because the required weld is more easily done with steel (stainless steel would be required for the battery cell) and the two-piece container is more commonly made with aluminum, which is more easily drawn than steel.

The cost of fastening the cover onto the cell would be most expensive for laser welding (assume $2.00/cell), less expensive for TIG welding ($1.50/cell), and least expensive for double seaming ($0.50/cell). Double seaming might also save an additional $0.50/cell in the cost of the container by avoiding the need for deep drawing.

Flexible packaging has a substantial cost advantage over rigid containers both in fabrication of the container and in sealing the container. This advantage for the Flex cells would be enhanced for a manufacturing facility that produced cells of several different sizes or occasionally changed the size of a cell. Although Rigid cell size requires retooling, a single stock of flexible packaging material will suffice for a wide range of Flex cell sizes and the pressing of pockets to receive the winding, if necessary, would require inexpensive tooling. The material cost, including formation of pockets to receive the windings, was estimated by a Japanese vendor in the flexible packaging industry at $0.40/cell. Sealing is estimated to cost an additional $0.20/cell.

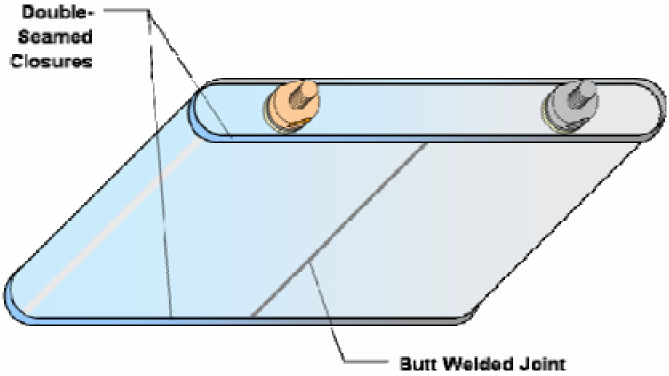


Figure 7. Three-Piece Rigid Container for Lithium-Ion Cell.

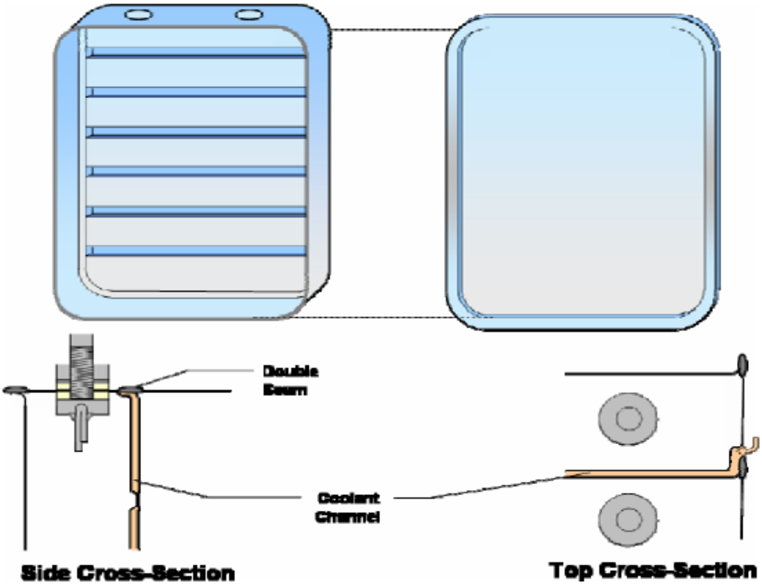


Figure 8. Two-Piece Rigid Container with closure on Side of Cell.

2.4. Cost of Terminal Fabrication and Sealing

The terminals for the Flex cells can be fabricated from sheet or strip stock. In the design study, the terminals were made of 1-mm-thick materials. Prior to cell assembly, it might be desirable to bend the terminals so that the negative and positive terminals of adjacent cells will be aligned for cell interconnection (Figures 1 and 4). A set of terminals was estimated to cost $0.40/cell by the Japanese vender mentioned above. The sealing of the terminals into the flexible package is not a separate operation, but is accomplished during sealing of the package. The seam in the top of the package through which the terminals extend is sealed by hot sealer jaws that are shaped to accommodate the terminals [1]. These procedures have already been demonstrated for Argonne by Sumitomo [1].

In contrast to the simplicity of fabricating and sealing the Flex cell terminals, the Rigid cell will require the development of new fabrication and sealing procedures. The most straightforward approach to terminal fabrication for the Rigid cell is to weld the sheet stock, to which the current collector foils will be attached, to the terminal feedthrough. The terminal feedthrough would have a threaded stud so that a seal could be made with the container by means of gaskets on both sides of the container that are compressed by tightening a nut (Figures 2 and 5). To minimize moisture intrusion, the gasketing material could be annealed nickel with a thin insulator adjacent to the container. In Figure 5, the terminal feedthrough is shown as a threaded stud with flats at the top of the threaded region so that it might be gripped when the nut is tightened to seal the unit. In order to improve electrical conductivity, the sheet stock is folded at the top where it is welded to the stud. Various approaches could be taken to developing improved terminals for Rigid cells. Single forged pieces might be developed that provide the function of the metal strip for attachment of the current collector’s foils and the function of the threaded feedthrough, thus avoiding the welding of these parts together. A special container top could be developed that seals directly to flat terminal strips similar to the sealing mechanism used for the terminals of the Flex cells.

Although the exact costs for the terminals have not been determined, it seems unlikely that development efforts will reduce the costs of the terminal fabrication and sealing for the Rigid cell to those for the Flex cell, which employs only flat strips and no special sealing procedures except as a part of the cell sealing. The cost of fabricating terminals for rigid cells and sealing them into the top of the container is estimated to be $1.50 to $2.00/cell, depending on the terminal design and the success of the development efforts.

2.5. Cost of Provision for Cooling Channels

Provision for cooling channels adjacent to the cells is important both for normal temperature control of the cells and as a safety measure during an internal short circuit, when a high cooling rate is desirable to avoid a more serious temperature excursion. Cooling with a dielectric transformer fluid that can withstand high temperatures would be more effective than air cooling. Cooling with air is less expensive, but not as safe. Both methods of cooling require attention to the thickness of the cooling channel for efficient cooling and acceptable pressure drop in the coolant circuit. The coolant is in laminar flow through thin, broad channels (about 1 mm x 20 mm) so that the Nusselt number (Nu) is about 8.24. (Nu = hDh/k, where h = heat transfer coefficient, Dh = 4 x flow area/perimeter, and k = thermal conductivity, all in consistent units.) Thus, the heat transfer coefficient at the surface of the cell is inversely proportional to the thickness of the cooling channel. Considering both pressure drop and cooling efficiency, the appropriate cooling channel thickness was found to be about 1.0 mm for both air and dielectric fluid.

Flex cells do not provide rigid surfaces for the walls of cooling channels. We propose to circumvent this problem by stamping rigid aluminum plates and folding them to enclose the flexible cells, and also to provide horizontal cooling channels (Figure 9). These cell covers would be about the same thickness (0.4 mm) and weight as the Rigid cell containers, but much less expensive because they are rapidly formed by shallow pressing with simple tooling. Their estimated cost is $0.50/cell.

Cooling channels for the Rigid cell are easily made by means of a polymer sleeve that slides over the cells to provide horizontal cooling channels (Figure 10). These sleeves could be made by stamping a polymer sheet for about $0.20/cell. We propose that the cooling channels be provided for the “sardine can” design in the shallow drawing step (Figure 8), but no additional savings is assumed because of the difficulty in comparing the overall cost of this design with that of the three-piece design, which would probably require a polymer sleeve to provide cooling channels.

2.6. Cost of Pressure Relief and Pressure Sensing

Many safety features need to be included in a realistic lithium-ion battery design. Battery safety is discussed in more detail in Appendix C, Safety and Monitoring.

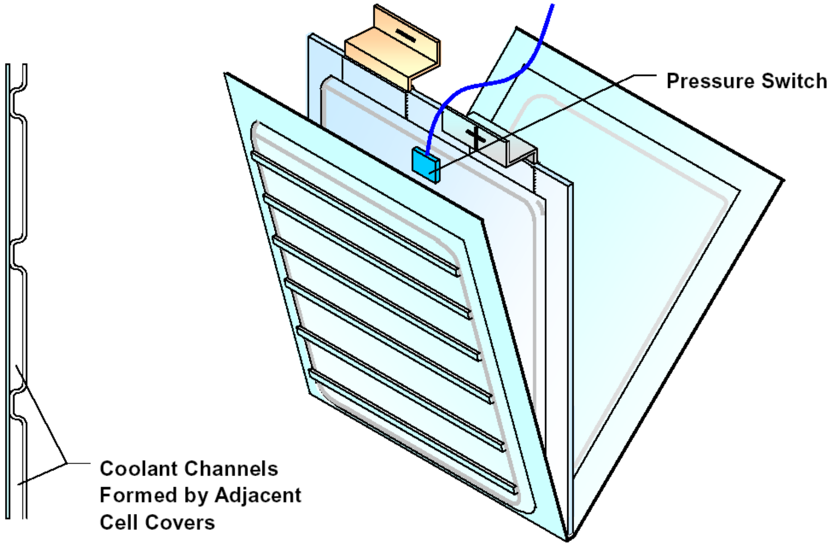


Figure 9. One-Piece Aluminum Cell Cover. Cover stamped from aluminum sheet to provide flow channels for coolant and support for flexible cell package.

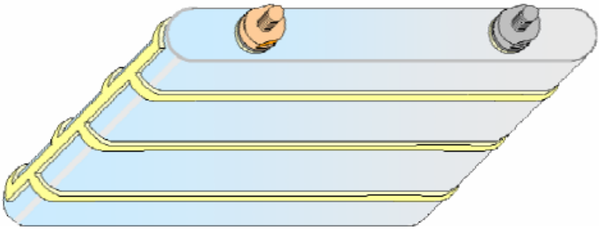


Figure 10. Rigid Cell with Sleeve that Provides Cooling Passages between Adjacent Cells.

Sensors measuring voltage and temperature are important for state-of-charge control and for taking action to avoid damage to the battery and the vehicle from, for instance, a malfunctioning battery controller, which may result in overcharging. An inexpensive pressure switch, if necessary, could be located outside of either the Flex cells or the Rigid cells to actuate a breaker to open the circuit in case of high pressure within a cell. All of these devices and those that they actuate to protect the battery would have about the same cost for both systems, and thus no difference in the cost of sensors is estimated for the two systems.

The cost of providing pressure relief, which is usually done by scoring the top or the bottom of rigid containers, is estimated to be $0.10 per cell. A similar method for weakening the side of a Flex container needs to be developed. Pressure relief through the seals of flexible packaging containers has been shown to take place over too wide a pressure range to be reliable. The total cost for providing both a pressure switch and pressure relief is estimated to be about the same for Rigid cells and Flex cells.

2.7. Cost of Intercell Connections

Forming a series connection of cells is easily done with Flex cells because the flat terminals can either be connected by ultrasonic welding or by use of a spring clip (Figure 4). The state-of-charge equalizing system can also be connected during either of these procedures. This can be done, for instance, by pre-connecting the spring clips to the state-of-charge controller so that the connection to that device is automatically made when the spring clips are attached to the terminals (Figure 11). For Flex cells, the cost of spring clip connectors and their attachment or ultrasonic welding of the terminals is estimated to be $0.20/cell.

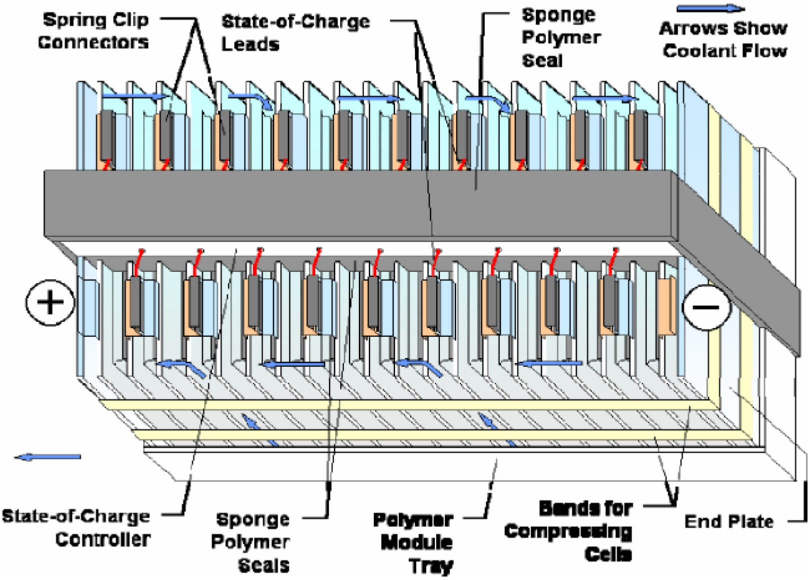


Figure 11. Module of Twenty Flexible Package Cells Showing Coolant Flow Pattern.

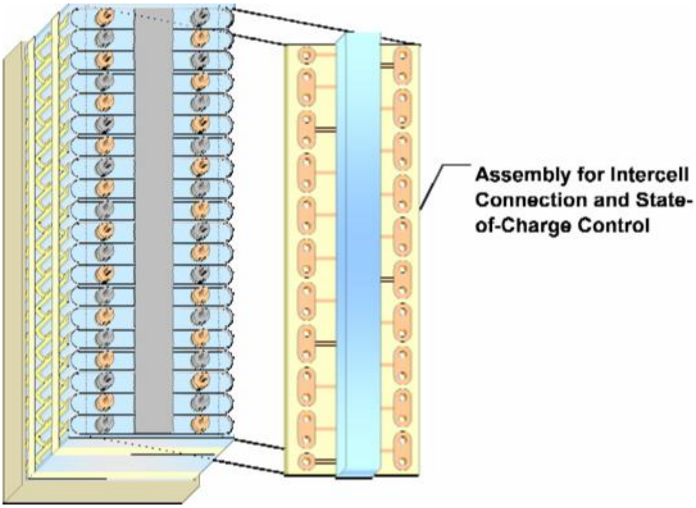


Figure 12. Module of Twenty Rigid Cells.

The threaded terminals of the Rigid cells require the use of a separate connector that is fastened to the terminals by threaded nuts. The connectors can be imbedded in a polymer plate that is attached to the state-of-charge controller and leads in this plate result in automatic connection of the cells to the controller (Figure 12). The cost of the connectors imbedded in the polymer plate and the attachment of this assembly to the terminals of the Rigid cells is estimated to be $0.50/ cell. This cost does not include that for the state-of-charge controller, which would be the same for both types of batteries.

Overall, the Flex cells appear to have a cost advantage over the Rigid cells in making intercell connections because the Flex cell terminals can be connected directly without the need for an additional connector piece. Bolted connections or spring clip connections may oxidize, and are more likely to require maintenance than welded connections. If welding of the intercell connectors is required to achieve 15-year life, it can be done more easily by ultrasonically welding of the flat Flex cell terminals than by any welding procedure for the Rigid terminals.

2.8. Cost of Module and Battery Hardware

The module and battery hardware can be practically identical for the two types of cells. The volume of the baseline Flex battery would be about three liters larger (28%) than that of the Rigid cell battery; about half of that volume is due to the extra coolant volume in the space near the seals. The weight breakdown for the battery parts for the two systems is shown in Figure 19. If air cooling were used, there would be very little difference in the total weights of the two types of batteries. With dielectric coolant there is a slight additional cost for the additional materials in the Flex cell battery (mostly additional coolant cost) of about $6.00 or $0.30/cell for a 20-cell battery.

3. COMPARATIVE COST SUMMARY

Overall, Flex cell batteries appear to have an advantage of about $1.20-$3.70 per cell for a 25-kW Battery of 20 cells, or about $24 to $74 per battery. The estimated cost advantages discussed above are summarized in Table 1.

Table 1. Cost Estimates in Comparing Flexible Package Cells (Flex) and Rigid Cells (Rigid).

	Cost, $/cell		
	Rigid	**Flex**	**Difference[a]**
Fabrication of cell windings	b	b	$0.00
Attachment of electrodes to terminals	c	c	0.00
Container fabrication and sealing	$1.00-3.00	$0.60	0.40-2.40
Terminal fabrication and sealing	1.50-2.00	0.40	1.10-1.60
Provision for cooling channels	0.20	0.50	(0.30)
Pressure relief and pressure switch	d	d	0.00
Intercell connections	0.50	0.20	0.30
Module and battery hardware	e	e + 0.30	(0.30)
Total cost advantage for Flex cells			1.20-3.70

a Cost for Rigid Cells minus that for Flex cells
b Cost of materials and fabrication for Rigid windings
c Cost of attaching Rigid cell electrodes to terminals
d Cost of providing pressure relief and a pressure switch for Rigid cell
e Cost of module and battery hardware for Rigid cells

4. RIGID CONTAINER WITH POLYMER-SEALED TERMINALS

As noted in Section 1, Introduction, personnel from Crown Packaging Technology suggested, late in our study, a design (Figure 3) that combines most of the performance and cost advantages of both the Rigid and Flex designs. The container is fabricated with two pieces cut from a tri-layered stock consisting of an inner sealant layer such as that used for flexible packaging, a rigid aluminum alloy sheet about 0.2-0.3 mm thick, and an outer layer that is electrically insulating. The pieces are shaped by stamping so that they enclose the cell and permit flat terminals to protrude between the container halves as for Flex cells. This stamping also makes ridges in one of the container pieces so that coolant passages are provided when the finished cells are strapped together into a module.

The container shells are fastened together by a simple mechanical closure at the sides and possibly the bottom of the cell. (The bottom would not require a seam if the container were made of one stamping instead of two and folded at the bottom.) These edge closures consist of a folded seam that is closed by stamping the entire closure after fitting the pieces together. After completing the mechanical closing of the container, the container can be sealed by heating the entire perimeter or by ultrasonic vibration to fuse the inner polymer layers. The seam will extend at the sides and bottom of the container by about 4 or 5 mm and provide a folded sealant width of 10 to 12 mm in these regions, about the same sealant width as that across the top of the cell, which includes the terminal seals. The width of these seals is important in slowing the rate of both water entry and electrolyte solvent loss. The aluminum layer is sufficiently thick to provide impermeability through the sidewalls.

APPENDIX A. DESIGN MODELING

The performances were calculated for 25-kW Flex cell and Rigid cell batteries by means of a Microsoft Excel spreadsheet with a technique previously developed in this program [1-4]. In this technique the performance of the cell winding is calculated from data determined in the laboratory on small test cells. The program calculates the dimensions and weight of each cell and battery component, the resistances of each element in the current collection system, and thermal management parameters. All parameters are calculated simultaneously so that a change in one input parameter will cause the recalculation of all parameters affected by that input parameter. The performances of five batteries are usually calculated on a single spreadsheet so that the effects of changing a single variable can be easily assessed and graphed.

In designing the batteries, certain parameters were held constant for all designs to assure that all batteries in the study would have equal performance and meet the FreedomCar standards for hybrid vehicle batteries. Selected input parameters are shown in Table A.1. The value in the table for the area-specific impedance (ASI) of the electrodes and separator was determined by experiments on small cells with an area of 15.5 cm^2.

The values set for the battery power and for the voltage at full power determined the resistance of a new battery to be 0.035 1 ohms. The number of wraps in the cell winding was examined as a variable. Design calculations were made for 18, 20, 23, 26 and 28 wraps around the flat winding core for both types of cells. The program calculated the resistance of the metallic conductors in the system and adjusted the area of the cells by changing the width of the cell in an iterative process (while holding the number of wraps and the height of the cell constant) until the battery resistance became 0.0351 ohms, matching that required of the set values for battery power and voltage. At the same time, the program automatically adjusted the cell loading density (Ah/cm^2) to match the input value of cell capacity, resulting in battery energy storage of about 1.6 kWh (evaluated at C/1 rate) for all cases.

Table A.1. Selected Input Parameters for Design Study.

Parameters	Input Value
Power for 10 seconds	
Rated (End of Life)	25 kW
New Battery (30% excess)	32.5 kW
Rated Regeneration Power (end of life)	20 kW
ASI of Electrodes and Separator for 10-s Power Burst	25 ohm-cm^2
Number of Cells, series connected	20
Open Circuit Voltage at Full Power	78 V
Voltage for Maximum Discharge Pulse	75% of OCV
Cell Capacity	20 Ah

Changing the number of cell wraps while maintaining the cell capacity at 20-Ah and the same winding height changes the width and thickness of the cell windings, as illustrated in Figure A.1 for Flex cells. The results are nearly identical for Rigid cells. Baseline designs with 23 wrappings around the core were selected for both types of cells after studying these results and the thermal management requirements discussed in Appendix B. The decision for 23 wraps was based primarily on the need to have a thin cell for efficient cooling for both types of cells and the minimum cell thickness required for making connections to the terminals. Selected parameters for the baseline cells are shown in Table A.2.

One factor in calculating the battery resistance is the resistance within the current collector foils. To determine this resistance, the impedance of a section of the cell winding that included one connection to the positive current collector foil and one to the negative current collector foil was calculated in a two-dimensional finite-element analysis (Flex PDE.4.0.6a by PDE Solutions, Inc.) for 59 cases covering a wide range of electrode dimensions. An area-specific impedance (ASI) was ascribed to the current collection system itself by subtracting the area-specific impedance of the electrodes and separators from that of the entire winding section. It was found that the value used for the area specific impedance of the electrodes and separator in the calculation had very little effect (<1%) on the net value calculated for the current collector system by this subtraction method. Also, whether both the negative and positive connections were on the top or one on the top and the other on the bottom had little effect. These results validated the approach of separating the measured value of the area-specific impedance of the electrodes and separator from the calculated area-specific resistance of the current collector foils. The resulting ASI for the current collectors was thus obtained for the 59 cases and empirically correlated (Figure A.2). For that study the ranges of variables, as defined below, were A, 200 to 1600 cm^2; H/W, 0.5 to 1.4; and T/W, 0.03 to 0.47.

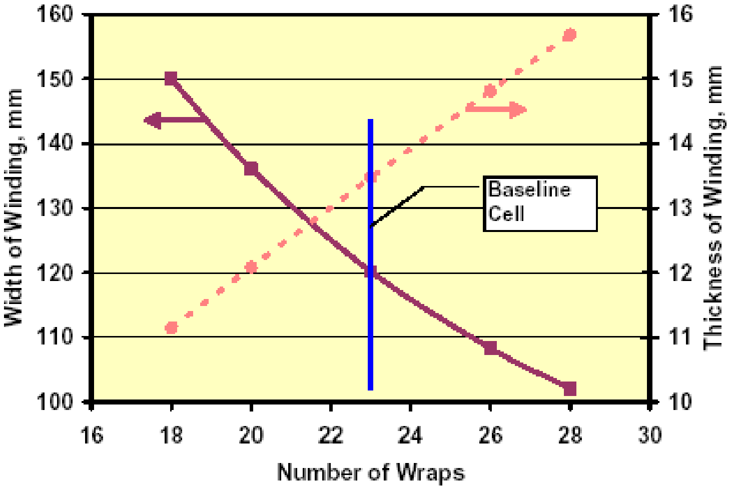


Figure A. 1. Effect of Number of Wraps on the Width and Thickness of 20-Ah Flex Cells.

Table A.2. Comparison of Parameters for Baseline Flexible Packaging and Rigid Cells for 25-kW Hybrid Vehicle Batteries.

Cell Parameters	Input Values	Flex	Rigid
Cell Capacity, C/1 rate, Ah	*	20	20
Positive Electrode First Charge Loading Density, mAh/cm^2		1 .37	1 .35
Negative-to-Positive 1 st Charge Capacity Ratio	*	1 .2	1 .2
Coefficient of Capacity Delivered, mAh/g	*		
Positive		178	178
Negative		338	338
Positive Electrode Composition	*		
Active material (LiNi1/3Co1/3Mn1/3O2), wt%		82	82
Carbon (total), wt%		1 0	1 0
Binder (PVDF), wt%		8	8
Electrolyte fraction, vol%		32	32
Positive Electrode Dimensions			
Thickness of coating (applied on both sides), µm		33	33
Width of coating, mm	*	150	150

Table A.2. (Continued)

Cell Parameters	Input Values	Flex	Rigid
Thickness of positive current collector, µm	*	30	30
Negative Electrode Composition	*		
Active material (graphite), wt%		92	92
Binder (PVDF), wt%		8	8
Electrolyte fraction, vol%		34	34
Negative Electrode Dimensions			
Thickness of coating (applied on both sides), µm		33	33
Width of coating, mm	*	153	153
Thickness of negative current collector, µm	*	1 8	1 8
Cell Winding Parameters			
Number of wraps	*	23	23
Height, mm		1 62	1 62
Width, mm		120	122
Thickness, mm		13.5	13.4
Thickness of core, mm		2.0	2.0
Total cell area, cm^2		16,379	16,603
Terminal Dimensions, mm			
Flex cell terminal width		38	
Flex cell terminal thickness	*	1 .0	
Rigid cell terminal threaded diameter	*		4.9
Cell Dimensions, mm			
Height		187	169
Width		144	123
Thickness		13.7	14.3
Cell Weight, g		65 1	724
Power Performance			
ASI for 10-s power pulse, ohm-cm^2		28.5	28.7
Cell rated power (end of life, 1 0-s pulse) at 25% SOC, W		1 ,254	1 ,256
Cell specific power for new cell, kW/kg		2.50	2.25
Cell Specific Energy (C/1 rate), Wh/kg		124	111

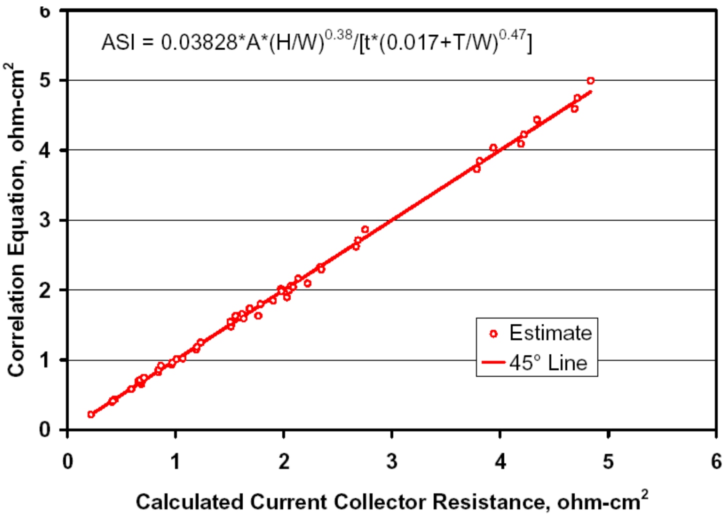


Figure A.2. Correlation of Results Calculated by the Partial Differential Equation System (Flex PDE.4.0.6a by PDE Solutions, Inc).

The following equation was found to fit the calculated values for the current collection system with an average error of 2.3%:

$$ASI = 0.03\ 828*A*(H/W)^{0.38}/[t*(0.0\ 1\ 7+T/W)^{0.47}],$$

where

ASI = area specific impedance of the current collector system, ohm-cm^2,
A = area of cell served by a single set of connections to terminal pieces, cm^2,
H = electrode height, cm,
W = width of area served, cm,
T = width of tab or terminal piece making connection to the current collector foil, cm, and
t = thickness of aluminum positive current collector foil with copper negative foil thickness of 18/30th that of the positive foil, µm.

To adapt this equation to a flat wound cell, the value of “A” is calculated by dividing the total area of the positive electrode by the number of windings (or twice the number of windings if there are two connections to each terminal piece for every winding). Similarly, the “H/W” ratio is calculated as the height of the positive electrode divided by the quotient of the total coated length of the positive electrode and the total number of connections to the positive terminal piece.

The correlation equation can be solved in the Microsoft Excel spreadsheet in less than one millisecond, whereas the PDE method requires several seconds. More than 1000 solutions of the equation are required to solve the spreadsheet for a set of five battery designs because the current collector dimensions change with each spreadsheet iteration (total time to solution: about 10 s).

A breakdown of the battery resistance for 20-Ah baseline Flex Cells and Rigid cells is shown in Figure A.3. The major resistance for both batteries is in the electrodes and separator. The resistances of the terminals and the inter-cell connections are slightly higher for the Rigid cells. The diameter of the threaded terminals is slightly less than desired because of the narrowness of the cell and the need to provide nuts in the space available. Inter-cell connections have higher resistance for the Rigid cells because of the need for an additional connector piece between the cells that requires two connections, whereas the terminals of adjacent Flex cells are connected directly with a spring clip or by ultrasonic welding. The effects of the slightly higher resistances of these items for the Rigid cells is that the area of the cells must be 1.4% larger than that for the Flex cells so that the total battery resistances will be the same, resulting in the same power for both battery types.

As noted above, changing the number of wrappings in the winding changes the dimensions of the cell windings. The Flex cells are wider and taller than the Rigid cells (Table A.2) because of the sealing region in the Flex cells. It is necessary to incorporate the sealing region into the coolant distribution channels to achieve a compact design. This is discussed in Appendix B, Thermal Management. In the battery designs for both the Flex cell and the Rigid cells, the modules are enclosed in an insulated jacket that is hermetically sealed and cooled by a dielectric liquid. Sponge polymer seals between the module and the jacket (Section 2.7, Cost of Intercell Connections, Figure 11) assist in directing the flow of coolant between the cells from one side of the jacket to the other. For the Flex cells, additional sponge polymer seals are shaped to fit the top and bottom of the cells (Figure A.4). The jacket is sketched in Figure A.5, which also includes a table of overall dimensions for the two baseline battery systems.

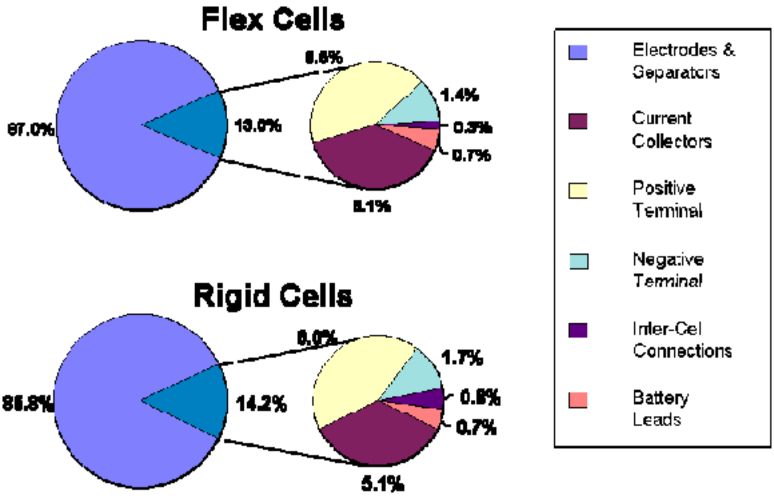


Figure A.3. Breakdown of Battery Resistance for Baseline Flex Cells and Rigid Cells.

The changes in cell dimensions caused by changing the number of cell wraps in the winding also affects the weight and volume of the batteries, as illustrated in Figure A.6. Over the ranges studied, these changes were not considered to be important in selecting the baseline cell designs. A breakdown of the weight of the battery parts for the Flex cell and Rigid cell batteries is shown in Figure A.7.

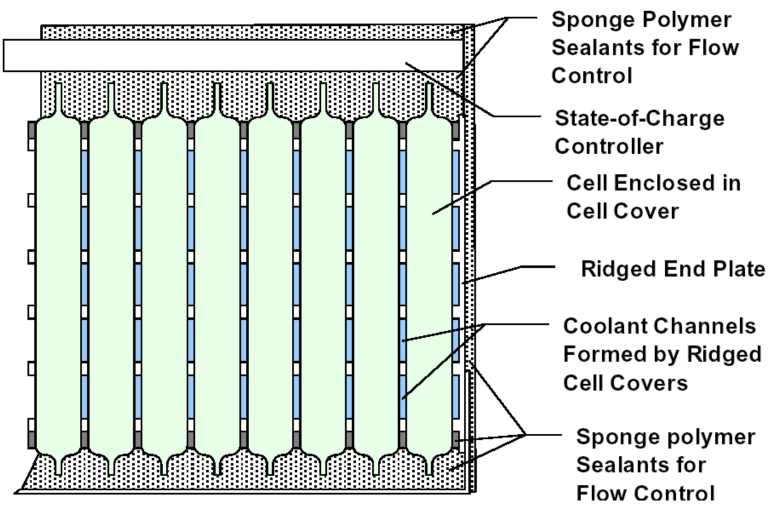
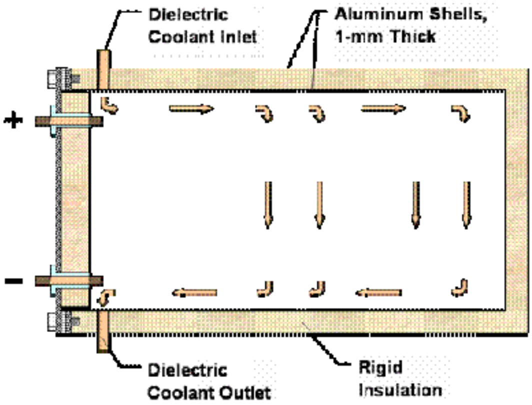


Figure A.4. Cross-Section of Flex Cell Module Showing Flow Coolant Flow Passages.



	Flex	Rigid
Length, mm	346	341
Width, mm	172	161
Height, mm	234	212
Volume, L	14	11
Weight, kg	20	19

Figure A5. Insulated Battery Jacket Providing Cooling with Transformer Fluid.

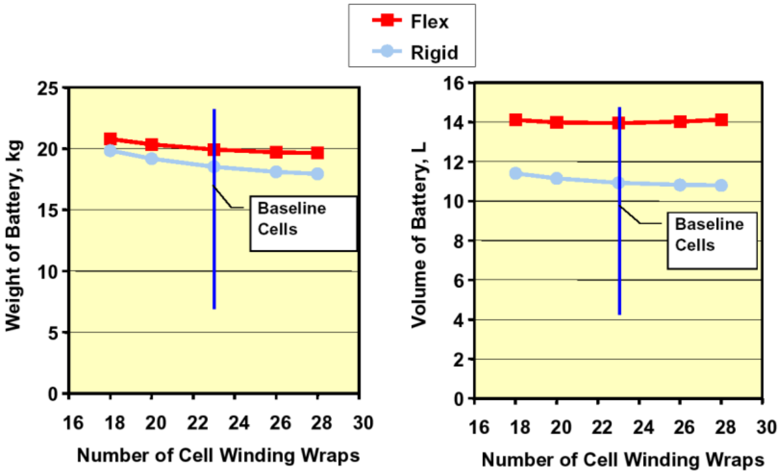


Figure A.6. Weight and Volume of 25-kW Batteries of Flex Cells or Rigid Cells.

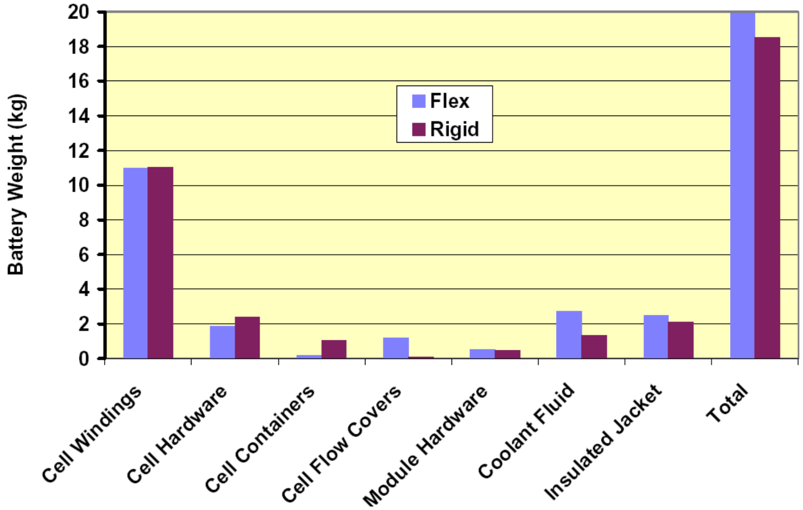


Figure A.7. Weight Breakdown for 25-kW HEV Batteries of Baseline Design.

APPENDIX B. THERMAL MANAGEMENT

Lithium-ion batteries for hybrid vehicles must have effective thermal management systems to avoid high temperatures, which may cause shorter cell life and lead to thermal runaway. It is apparent that the lower the temperature is maintained during operation and standby, the lower will be the rate of those deleterious effects to the battery that are inhibited only by chemical kinetics rather than the condition of thermodynamic stability. During cell malfunctions, high cell temperatures may lead to thermal runaway, which in many cases could be avoided by an efficient cooling system.

Maintaining the temperature as low as 10°C, at which the power is only slightly reduced from that at room temperature, would be beneficial for the battery life. Fortunately, the lithium- ion system is very powerful and the batteries in this study were designed to have excess power through most of their lives so that they can still achieve full power near end of life [1]. The design program that we use at Argonne National Laboratory designs the battery with 30% excess power (Appendix A, Table A.2) based on laboratory tests of the electrodes at 25°C. It is estimated that at 10°C a new battery could achieve about 120% of the full design power. A strategy for achieving long life, therefore, is to control the normal operating temperature at only 10°C and to raise the control temperature near the end of battery life to maintain the full design power. This strategy requires the use of refrigeration. For the batteries in this study, a dedicated refrigeration system would only need to produce about 160W of cooling, less than 2% of the maximum load on the air conditioning system for cooling the vehicle interior. This amount of cooling for the battery can be achieved by a compression system about the size of that in a student refrigerator or, at lower efficiency, by a thermal-electric system.

Another matter for concern is the response of the thermal control system to extreme ambient temperatures. The use of thermal insulation and control will help to avoid reaching high temperatures during parking on a sunny summer day (when the temperature in some parts of the vehicle may reach 60°C) if the battery temperature prior to parking is only 10°C (Figure B.1). After exposure to very cold ambient temperatures (down to -30°C) the battery would have sufficient power to start the vehicle and it could be heated sufficiently to achieve full power in about 5 to 10 minutes by heaters in the coolant circuit.

Both air and a dielectric liquid, such as Dow Corning 651 Transformer Fluid, were considered as coolants for this study. The initial cost is lower for air cooling than for dielectric cooling. With air cooling the requirement for a dedicated refrigeration system might be avoided by use of the air conditioning (AC) system in the vehicle to cool the battery with air diverted from that directed to cool the vehicle interior or by diverting refrigerant fluid from the compressor outlet to a separate evaporator to cool the battery coolant.

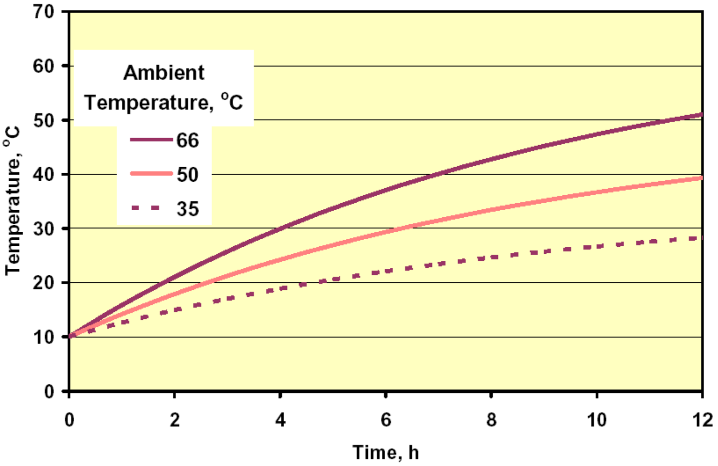


Figure B.1. Heating of Battery during Standby for Various Ambient Temperatures.

The efficient cooling of the battery during operation under normal conditions and cell failure conditions requires the use of forced cooling with thin coolant flow passages provided adjacent to the cells. Because the Flex cells and the Rigid cells are so similar in their dimensions and compositions, there is virtually no difference in their thermal performance. The Rigid cells are designed with a 40-μm polyimide layer between the electrodes and the electrically conductive container, which is not necessary for the Flex cells. However, the Flex cell container is less thermally conductive than the Rigid container. Both of these factors were taken into account, but the heat transfer across the cell layers per unit of temperature difference was calculated to be virtually the same for both types of baseline cells (4.7 W/°C for the Rigid cell and 4.6 W/°C for the Flex cell).

Some of the input parameters and the results of the thermal analysis are shown for the baseline Flex cells in Table B.1. The target heat rejection rate of 161W, which is equivalent to a 90% efficiency discharge at the C/1 rate, is a conservatively high rate of heat generation for a rigorous driving profile. The pressure drop for circulation of the coolant through the battery (Table B.1) is satisfactorily low so that the sealed battery jacket (Appendix A, Figure A.5) can easily withstand the pressure. The power required for the fan to deliver air coolant to the battery would be much higher than that required for the pump to circulate the dielectric fluid even though the design temperature rise for the air coolant is four times as high as for the dielectric fluid. The temperature rise through the air film on the surface of the cell is much higher than through the dielectric fluid film. This is further illustrated in Figure B.2, in which the temperature rise is plotted as a function of the number of wraps in the cell winding (the baseline cell has 23 wraps) for both air cooling and dielectric fluid cooling for the target rate rejection rate of 161 W discussed above.

The advantages of cooling with a dielectric fluid are especially apparent for cooling a malfunctioning cell. If a cell develops an internal short circuit or begins to generate heat at a high rate for some other reason, both a low temperature difference between the cell centerline and the coolant and a low temperature rise for the coolant in passing over the cell become important safety factors that will permit a large increase in the heat rejection rate from the cell.

Since no more than one cell is likely to malfunction at any one time and the coolant from the malfunctioning cell is mixed with that from the other cells, the cooling system can handle a heat generation rate in the malfunctioning cell that is many times larger than the design rate. As the heating rate in the malfunctioning cell rises well above the design cooling rate, the difference between the temperature at the center plane of the cell and that of the coolant increases and the temperature of the coolant as it leaves the cell increases. The maximum temperature at steady state occurs at the center plane of the cell near the end of the coolant passage. The dielectric coolant is more effective than air because of its higher thermal conductivity, which results in lower cell surface temperatures (Figure B.3), and its higher heat capacity, which results in a lower temperature rise for the coolant. If the total electrochemical energy in the cell is converted to heat at a constant rate, then the maximum steady-state temperature in the cell will be much higher for air cooling than for dielectric fluid cooling and these temperatures will depend on the energy conversion rate (Figure B.4).

Factors in favor of dielectric coolant rather than air include (1) more effective cooling, especially during cell malfunctioning with high rates of heat release; (2) a cleaner coolant system unaffected by dust, moisture, ozone, and salt spray in the ambient air; (3) lower power for circulating the coolant, which has a value over the life of the battery that is at least as high as the initial cost of the dielectric coolant; and (4) non-combustion in the event of a cell breach and exposure of the cell interior to the coolant.

Table B.1. Thermal Management Parameters for 25-kW Hybrid Vehicle Batteries with Flexible Package Cells.

	Dielectric Fluid	**Air**
Cell Dimensions, mm		
Height	187	
Width	144	
Thickness	14	
Number of Cells	20	
Coolant Channel Thickness, mm	1.0	
Target Heat Rejection Rate for the Battery, W	161	
Coolant Temperature Rise Across Each Cell, °C	1.0	4.0
Coolant Flow Rate per Cell, g/min	321	122
Pressure Drop in Coolant System, bar		
Through passages between cells	0.019	0.0023
Balance of system	0.100	0.003
Power to Motor for Pump or Fan, W	1.9	30.3
Temperature Rise above Coolant Temperature, °C		
To surface of cell	0.4	2.4
To center of cell	2.3	4.3

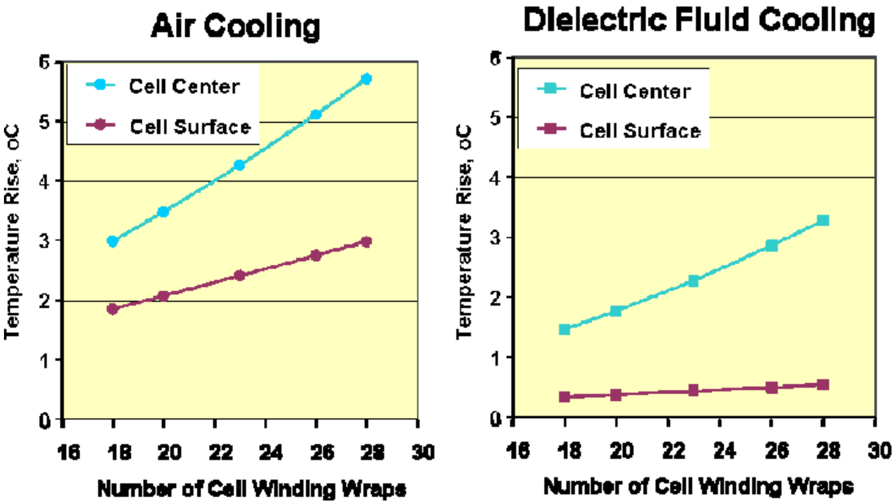


Figure B.2. Temperature Rise above that of Adjacent Coolant for Flex Cells.

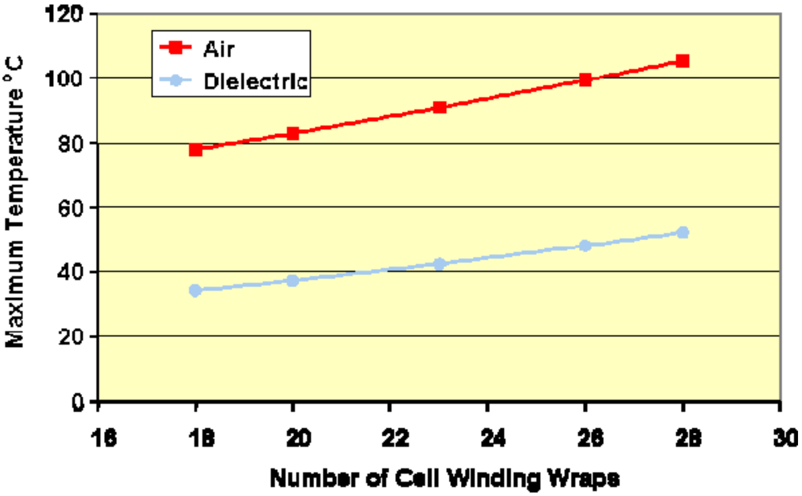


Figure B.3. Maximum Temperature Reached at Center of Flex Cell during Malfunction that Converts Total Electrochemical Energy of Fully Charged Cell to Heat at C/1 Rate with Coolants at 10°C Inlet Temperature.

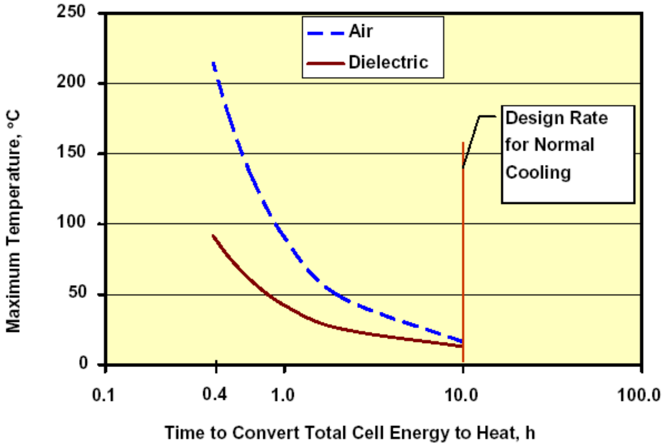


Figure B.4. Maximum Temperature Reached at Center of Base Line Flex Cell (23 wraps) as Function of Heat Generation Expressed as the Time to Convert the Total Electrochemical Cell Energy to Heat with Coolants at 10°C Inlet Temperature.

APPENDIX C. SAFETY AND MONITORING

Gases are generated within lithium-ion cells during normal operations such as formation cycling and charging and during abuse conditions such as overcharging and overdischarging. The cells must be designed to withstand the pressure for normal and mild abuse conditions, but relieve high pressures of two or three atmospheres. Relief of pressure has been accomplished by the use of rupture discs for both prismatic and cylindrical cells [1]. Flex cells can also be designed to release at the desired pressure [2]. The testing of Flex cells for gas release under abuse conditions must be done with the aluminum cell covers in place since these covers are clamped together by the endplates and straps in the module, which may interfere with the release of pressure for some designs (Section 2.7, Cost of Intercell Connections, Figure 11).

Another safety device has been developed for both cylindrical and prismatic lithium-ion cells that breaks the aluminum lead from the positive electrode to the positive terminal when actuated by high internal cell pressure [1]. The breaking of the lead stops the abuse before the temperature and pressure become so excessive that the cell ruptures. A similar device has been proposed for cells for hybrid-electric vehicle (HEV) batteries, but for a battery of many cells in series the use of such a devise is inadvisable. The ends of the broken lead would have the full battery voltage impressed on them in the presence of electrolyte and possibly oxygen from the positive electrode, which might result in an explosion due to arcing across the broken lead.

It may be possible to incorporate safety devices into Flex cells of the same type as have been proposed for the rigid cells. The flexible packaging itself would not interfere with such a mechanism. For the same cell chemistry and cell capacity, the cross-section over which the actuating force would be generated for breaking of an internal cell lead would be the same. However, the design of the mechanism might be easier for cylindrical cells than for prismatic cells.

A more promising approach for dealing with high cell pressures is the use of a pressure- sensitive switch located, for instance, between the flexible package and the rigid aluminum cover (Section 2.5, Cost of Provision for Cooling Channels, Figure 9). A high pressure in the cell would actuate the switch and cause the main battery breaker to open. Because of the flexibility of the cell container, the pressure between the cover and the Flex cell is essentially the same as that within the cell. If the abuse condition is detected and corrected after the pressure switch has actuated, the abused cell will still be functional, whereas actuation of a device within the cell, for instance to break the lead to the positive current collector, is not reversible and will result in the loss of the cell and the loss of the entire module, since replacement of a cell within a module is impractical.

This approach may also be applicable to some Rigid cell designs having somewhat flexible sides, permitting actuation of a pressure switch outside of the cell. The location of the switch for best results could be determined in a test program. An external pressure switch could not be easily applied for a cylindrical cell, which is too rigid.

The proposed pressure-activated device for actuating the main battery circuit breaker for both the Flex cell and the Rigid cell would be in addition to other safety measures. These measures should include: (1) automatic state-of-charge equalization of cells during periods of battery inactivity longer than 15 minutes; (2) redundant monitoring and control of the battery voltage to avoid overcharging of the battery; (3) voltage monitoring of each cell with warning lights and opening of the main battery circuit breaker, if warranted; (4) temperature monitoring of each coolant passage between cells, which would give a separate distress signal for each side of the cell (providing redundancy), with action taken at high temperature; (5) high-efficiency cooling for high cell temperatures caused by cell abuse or cell malfunctioning, with the capability of removing heat at ten times the design rate for normal vigorous battery operation.

APPENDIX D. COMPANY CONTACT INFORMATION

Following is an alphabetical list of companies, with associated contact information:

Company Information	*Contact*
CROWN Packaging Technology, Inc. 11535 South Central Avenue Alsip, IL 60803 Tel: 708-239-5273 Fax: 708-239-5453 E-mail: mike.gredlics@crowncork.com Internet: www.crowncork.com	Mike Gredlics
Flex-Pak Packaging Products, Inc. 651 N. Raddant Rd. Batavia, IL 60510 Tel: 630-761-3335 Fax: 630-761-3336 Internet: www.flex-pak.biz	William Reimann
Integrated Solutions 3242 Monroe Street Waukegan, IL 60085 Tel: 847-623-3695 Fax: 847-623-3726 E-mail: rhinoje@aol.com	James Rinehart
Plastic Technology Partners 605 Leesburg Ct. Naperville, IL 60540 Tel: 630-357-2894 E-mail: scornell.ptp@juno.com	Stephen W. Cornell
Sumitomo Electric Flat Components, Inc.	Takehiro Hosokawa

(A subsidiary of Sumitomo Electric
Industries, LTD.)
3-3, Satsuki-cho, Kanuma,
Tochigi, 322-8585 Japan
Tel: 0289-76-0334
Fax: 0289-76-3485
E-mail: hosokawa@sei.co.jp
Internet: www.sei.co.jp

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Chapter 4

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

***Argonne National Laboratory
and Energy Systems Division***

ABSTRACT

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

emissions, and criteria pollutant emissions. Some process-related emissions are also reviewed in this report.

1. INTRODUCTION

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

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

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

The preferred approach to environmental evaluations of product systems is life-cycle analysis (LCA) (ISO 14040, 14041, and 14042) (ISO 1997, 1998, and 2000). The LCA is a method that provides a system-wide perspective of a product or service — one that considers all stages of the life cycle, including material production, system manufacture and assembly, service provision, maintenance and repair, and end-of-life processes. Though generally the objective of an LCA is a cradle-to-grave evaluation, in this study the focus is on cradle-to-gate (CTG) assessments.

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

2. EVALUATION CRITERIA

The evaluation of battery life-cycle studies reviewed herein is based on a process life- cycle assessment framework. More specifically, the evaluation places a high value on studies where detailed process-specific data are presented; ideally, those where unit process flows have been either provided or referenced. A representation of the flows required to characterize a unit process is depicted in Figure 1. Typically, numerous such processes are required to manufacture most products. For example, in making a PbA battery, unit processes are needed for the production of lead, acid, battery cases, poles, separators, copper, and other components, as well as one or more processes for putting it all together into a purchase-ready product. Further, the production of materials also requires a number of unit processes. For example, the unit processes required to produce lead are mining, beneficiation, ore preparation, smelting, and refining.

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

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

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

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

$$\{B\}_{ctg} = \{B\}_{mp} + \{B\}_{mnf}, \quad (1)$$

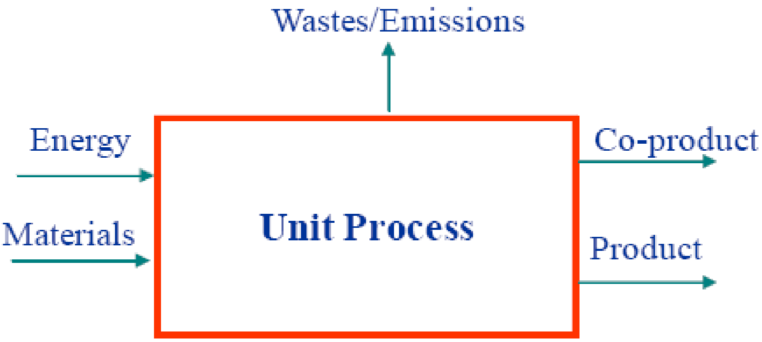

Figure 1. Generalized Unit Process.

Figure 2. Boundaries Assumed for the Cradle-to-Gate Study Evaluation.

where ctg denotes cradle-to-gate, mp stands for material production, and mnf indicates manufacturing. {B} is a vector quantity comprised of a number of components “Bi”, with each representing a particular environmental burden for the battery. Examples of such burdens include the emissions of CO_2 and the consumption of iron ore, natural gas, and water, as well as many others. Because products are usually composed of a number “n” of materials “j” in amounts of “mj”, the environmental burdens associated with the production of these materials must be quantified. For example, PbA batteries contain lead, lead peroxides, lead sulfate, sulfuric acid, water, plastics, and glass. Hence, the burden vector for material production of a battery is, in matrix notation:

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

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

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

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

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

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

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

Table 1. Key Properties of Various Battery Technologies.

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

Sources: Rantik 1999 and Rydh 2005.

[a] EV = electric vehicle; PV = photovoltaic energy.

[b] Cycle life at 80% depth of discharge.

[c] Cycle life at 33% depth of discharge.

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

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

Battery	Note	E_{mp}	E_{rcycl}	E_{mnf}	E_{ctg}	Reference
NiMH		108	19.6	8.1	119	Ishihara et al. (website)
					230	Ishihara et al. 1999
	AB_2				246	Gaines et al. 2002
					195	Gaines et al. 2002
	AB_5				263	Gaines et al. 2002
		57				Gaines and Singh 1995
		54–102	21–40[b]	74–139	128–241	Rydh and Sanden 2005
				14.6		Rantik 1999
		86.5		105	191.5	GREET 2.7
PbA		25.1	8.4	11.3	36.4	Ishihara et al. (website)
				77		Ishihara et al. 1999

Table 2. (Continued)

Battery	**Note**	E_{mp}	E_{rcycl}	E_{mnf}	E_{ctg}	**Reference**
		24.7				Gaines and Singh 1995
		15–25	9.0–14.0[b]	8.4–13	23.4–38	Rydh and Sanden 2005
				16.6		Rantik 1999
		16.8		6.7	23.5	Kertes 1996
		17.3	Included	8.81	26.1	Hittman Asso-ciates 1980
NiCd		102.8				Gaines and Singh 1995
		44.0		53.9	97.9	Kertes 1996
		44–60	22–30[b]	46–63	90–123	Rydh and Sanden 2005
Na/S		59.9				Gaines and Singh 1995
		179		56	235	Hittman Asso-ciates 1980
		82–93	30–34[b]	62–70	144–163	Rydh and Sanden 2005
Li-ion	NCA-G	93.3	4.8	32	125.3	Ishihara et al. (website)
	LMO-G	113	3.6	30	143	Ishihara et al. (website)
	NCA-G	53–80	25–37[b]	96–144	149-224	Rydh and Sanden 2005
		112.9		91.5	204.4	GREET 2.7
						Umicore Slide/ Virgin
	NCA-G				222[c]	Materials
						Umicore Slide/Recycled
	NCA-G				62.9[c]	Materials

[a] See Section 3.1.4 for Li-ion nomenclature; $_{\mathrm{Ercycl}}$ denotes energy to recycle the battery; see Table A-1 for megajoule/watt-hour values.

[b] Reported as material production energy using recycled materials.

[c] These values are per cell.

3. ENERGY ANALYSIS

3.1. Materials Production

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

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

3.1.1. Lead-Acid Batteries

The PbA batteries have been in use for more than a century, primarily as an automotive starter battery. During that time, they have undergone steady improvements in efficiency, durability, and lifetime. The chemistry remains unchanged. The main components of the battery are: a cathode comprised of lead peroxide on a lead lattice for support; an anode made of sponge lead, also on a lead lattice; an electrolyte of water and sulfuric acid; fiberglass matte (with some polymeric binders) separators that keep the anode and cathode apart; and a containment case, typically made of polypropylene. During discharge, lead at the cathode is reduced ($PbO_2 \rightarrow PbSO_4$), whereas at the anode it is oxidized ($Pb \rightarrow PbSO_4$). During recharging, these two reactions go in the opposite direction. The composition of a typical PbA battery is given in Table 3.

Table 3. Composition for a Representative Lead-Acid Battery.

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

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

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

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

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

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

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

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

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

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

3.1.2. Nickel-Cadmium Batteries

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

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

Table 5. Materials in an Automotive Nickel-Cadmium Battery.

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

[a] Source: Gaines and Singh 1995. shown in Table 5.

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

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

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

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

With the exception of Cd, the PE_j values given in the table are quite reliable. The values come from a set of references that collectively provides adequate production energy values and process details from a life-cycle perspective. From those PE_j values, and assuming a composition of (Cd, Ni, $Ni(OH)_2$, KOH, nylon, steel)% = (25,20,17,5,3,16)%, the E_{mp} for NiCd batteries is estimated to be about 98 MJ/kg, which is at the high end of the ranges shown in Table 2. Incidentally, one expects a range of E_{mp} values for these and other batteries. After all, E_{mp} values are dependent on battery material composition, which in turn is dependent on the application. For example, in contrast to the value just given, we estimate an E_{mp} equal to 84.2 MJ/kg for a small consumer product battery with the composition of (16, 21, 8, 4, 4, 39)% (Rydh and Karlstrom 2002).

3.1.3. Nickel-Metal Hydride Batteries

These batteries have become very popular, especially for power tools and hybrid vehicle applications. As seen in Table 1, these batteries have a better specific energy than NiCd batteries, and they do not suffer from a memory effect. The NiMH batteries have displaced NiCd batteries in many applications, especially in the hand-held power tools market. The components of the batteries are: a cathode comprised of nickel hydroxyl oxide, an anode of mischmetal (Me) hydrides, an electrolyte of KOH, and a separator of a porous polypropylene membrane. During discharge, the reaction at the cathode is the same as that for NiCd batteries; that is, the Ni is reduced ($NiOOH \rightarrow Ni(OH)_2$) and the mischmetal is oxidized ($MH \rightarrow M$) at the anode. Mischmetals are metals from the lanthanide series, or rare earths, including metals from lanthanum (atomic number = 57) to luterium (71), which in the context of batteries are referred to the AB5 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 AB2 type, which includes titanium (Ti), zirconium (Zr), Ni, and vanadium (V).

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

The PE_j data for this battery's materials are given in Table 6. Unfortunately, there are scant data in the literature on the production of mischmetal. The only reference found for this study was published by Ishihara et al. (1999). As seen in the table, their value, which is a result of their "hybrid analysis" (a combination of process LCA and EIO), is very high. If U.S. grid electricity were used to make this metal, the production energy would be 545 MJ/kg. To put this into perspective, the production energy for aluminum is 154 MJ/kg, which is a well-established value and on the high end for metal production.

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

3.1.4. Lithium-Ion Batteries

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

Table 7. Significant Materials in Representative Nickel-Metal Hydride Batteries.

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

[a] FromRantik 1999.

Table 8. Composition of Lithium-Ion Batteries.

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

[a] Source: Gaines and Nelson 2009.

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

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

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

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

In Table 8, it should be noted that the percent by weight of electrode materials varies considerably. This is related to battery capacity; as battery capacity increases, the amounts of cathodes and anodes also increase. Because battery operation is a result of chemical reactions, greater capacity means more reactions, which occur in the electro-active materials of the electrodes. For an LiCoO2 cathode and an LiC6 anode, a representative set of reactions during discharge is: cobalt is reduced (e.g., CoO2 → LiCoO2) at the cathode and LiC6 → C6 at the anode.

A summary of PE_j values for materials that comprise Li-ion batteries appears in Table 9. An inspection of the table reveals a considerable dearth of energy information on Li-ion battery materials, whether for anodes, cathodes, or electrolytes. More specifically, PE_j data for Li-ion battery constituent materials, such as LiNi0.8Co0.15Al0.05O2 and most of the other materials listed in Table 8, are sorely lacking. More information is needed about the reaction pathways from the commodity materials to the materials that make up the battery components listed in Table 8. Because of this, we are unable to estimate the material production energy for these batteries. Nevertheless, some energy data for these batteries are listed in Table 2.

3.1.5. Sodium-Sulfur Batteries

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

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

Overall, material production energy values for Na/S battery constituent materials are quite good, except for the ceramic b -alumina. The PE_j values shown in the table for the ceramic are both high and variable. As such, they are expected to affect estimates of battery $E_{mp.}$ If fact, by employing the PE_j values in the table, including the highest b -alumina value, the battery's E_{mp} is estimated to be 159 MJ/kg. On balance, this is much higher than the values found in Table 2 for the Na/S battery. If instead we use an alternative PE_j value for J3-alumina, the average of the other set (Gaines et al. 1995) given in the table, the E_{mp} becomes 80 MJ/kg. This value is in much better accord with the corresponding results given in Table 2. However, because of the magnitude and hence the significance of b -alumina's PE_j value on the $E_{mp,}$ a more reliable value is clearly needed.

Table 10. Material Composition of Sodium-Sulfur Batteries[a].

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

[a] Source: Hittman Associates 1980.

[b] ABB.

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

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

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

3.1.6. Summary of Results

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

3.2. Battery Manufacturing

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

3.2.1. Lead-Acid Batteries

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

3.2.2. Nickel-Cadmium Batteries

There is some LCI information on the manufacturing of NiCd batteries. Rydh and Sanden (2005) cite a range of values for $_{Emnf:}$ 46–63 MJ/kg of battery (see Table 2). However, they did not discuss manufacturing processes. The manufacturing processes required to make these batteries are as follows (Kertes 1996): (1) deposit and sinter carbonyl Ni powder in a reduction furnace onto the cathode metal strip to form sponge nickel; (2) impregnate the resulting cathode strip with Ni(NO3)2 for subsequent conversion to $Ni(OH)_2$; (3) press and roll plastic-bonded (PTFE) Cd with some graphite (to increase porosity and hence conductivity) onto the anode substrate (nickel wire mesh); (4) make the separators (three thin strips of polymer: nylon/ polypropylene/nylon); (5) charge the electrodes in excess electrolyte; (6) stack alternating layers of cathode and anode separated by a separator strip; (7) mold the polypropylene case; and (8) add components to the case, including the electrolyte and seal. This set of processes applies to either prismatic or jelly-roll configured batteries. Energy and emissions data are available for only a few of these processes.

3.2.3. Nickel-Metal Hydride Batteries

A summary of life-cycle energy values for NiMH battery manufacturing is given in Table 2, where a number of values of E_{mnf} are recorded. In an online document, Ishihara et al. (website) estimate the $_{Emnf}$ for a 59 Wh/kg battery to be about 8.1 MJ/kg, which is about 9% of the E_{ctg} value (94 MJ/kg of battery), also given there. However, in a separate report (Ishihara et al. 1999) they present a higher value of E_{ctg} (230 MJ/kg). The reason for the large difference in the two values is unknown. Others have also estimated the production energy of NiMH batteries. Based on European data (Kertes 1996), Rydh and Sanden (2005) report E_{mnf} values for NiMH batteries that range between 74 and 139 MJ/kg of battery. For the latter, no process details have been given. In a proprietary report, Gaines estimates the E_{mnf} to be a little higher.

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

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

3.2.4. Lithium-Ion Batteries

The manufacturing of these batteries consists of a number of processes that include: (1) preparation of cathode pastes and cathodes from purchased lithium metal oxides, LiMexOy, (Me = Ni, Co, Fe, Mn), binders, aluminum strips, and solvent; (2) preparation of anodes from graphite pastes and copper strips; (3) assembly of anodes and cathodes separated by a separator strip; (4) addition of electrolyte; (5) charging of cells; and (6) final assembly. For more detail, see a discussion by Gaines and Cuenca (2000) on these manufacturing steps. As seen in Table 2, Li-ion $_{Emnf}$ values are quite variable. Indeed, a review of the table reveals a low set of values around 30 MJ/kg and a high set greater than 100 MJ/kg. The low set is based on the work of Ishihara (website), and the high set is from Europe and North America. Ishihara (1996) details the manufacturing processes, including the production of solvent, LiNiO2, LiPF6, indirect effects, and assembly. On the other hand, the sources of the data in the high set provide no process detail.

3.2.5. Sodium-Sulfur Batteries

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

3.2.6. Summary of Battery Manufacturing Results

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

3.3. Recycling of Batteries and Battery Materials

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

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

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

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

Only one open literature reference was found that cites a value for material production of recycled Ni (see Table 6). In a proprietary report by Gaines et al. (2000), there is another value, which is slightly lower than the value shown in Table 6. Taking the PE_j for recycled Ni from Table 6 and applying it to all Ni in the battery, including $Ni(OH)_2$, we estimate E_{mp} for the NiCd battery to be 42 MJ/kg, which is half that estimated for the battery made from virgin materials. Depending on the validity of the PE_j for recycled Ni, battery material production energy is significantly reduced, and it could be even lower if Cd and the other constituent materials come from the recycling stream. We also expect it to have the same impact on NiMH battery material production. By applying these same recycled Ni production energy values to the NiMH battery, the E_{mp} is reduced by 36 MJ/kg, relative to that based on virgin materials. This is a significant reduction and, like that for the NiCd battery, could be even larger, if more of this battery's materials came from the recycling stream.

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

Umicore, an advanced materials company, has major operations devoted to battery recycling. Their primary interest is to recover Ni and Co, the latter of which currently commands high returns in the secondary marketplace. Although at this time Umicore does not recover the Li derived from Li-ion batteries, they could do so in the future if lithium prices in the secondary market become attractive. In fact, the battery recycling industry has concerns about the reduction of cobalt use in Li-ion batteries, since reduced yields of Co in that recycling stream could make their processes uneconomical. For Li-ion batteries, Umicore breaks up the batteries, feeds them into a smelting furnace, where metals are recovered, and subsequently sends them to a refiner to get the desired purity of Cu, Fe, Zn, $Ni(OH)_2$, and $CoCl_2$. The $CoCl_2$ is sent to another operation to produce LiCoO2 for use in new batteries. Umicore claims that using recycled Co reduces the production energy for $LiCoO_2$ by 70%. This is a tremendous improvement.

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

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

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

3.4. Cradle-to-Gate Life-Cycle Energy Comparisons of the Batteries

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

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

The material production results in Table 2 for all batteries, except PbA, are assumed to be from virgin sources. The PbA batteries have long used recycled Pb, and the values listed in Table 2 and Figure 3 already have recycled content implicitly included. However, even if PbA batteries were made using strictly virgin materials, their $_{Ectg}$ value (≈40 MJ/kg) would still be considerably lower than those of the other batteries. Incidentally, using the data of Rydh and Sanden (2005) and their E_{mp} values for recycled materials, we estimate that the $_{Ectg}$ would decrease by about 25%, 30%, 25%, 36%, and 20% for NiMH, PbA, NiCd, Na/S, and Li-ion batteries, respectively. Though these improvements are substantial, the values must be considered provisional due to uncertainty about the PE_j values for recycled battery materials.

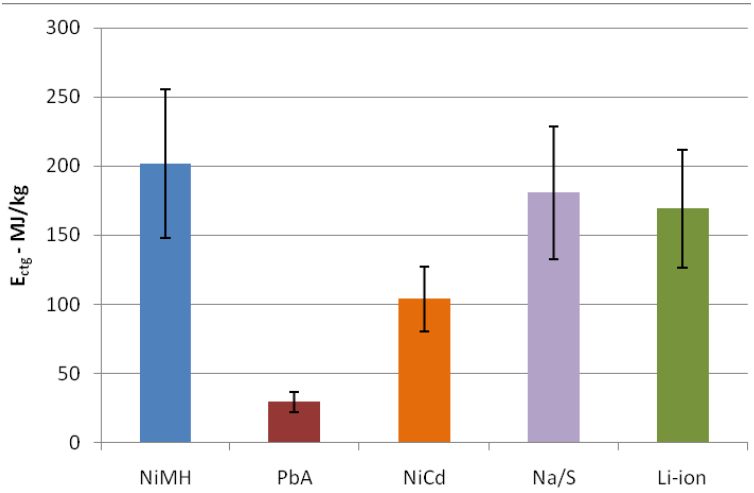

Figure 3. Average $_{Ectg}$ Values ± One Standard Deviation for the Various Battery Technologies (the materials production component is solely from virgin sources, except for PbA).

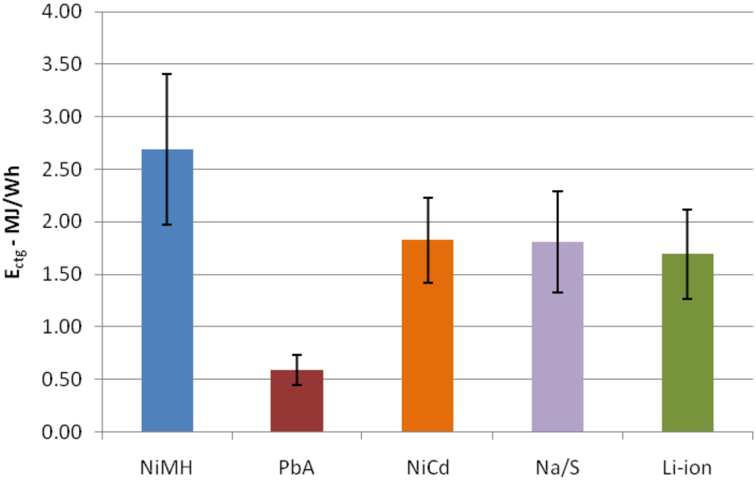

Figure 4. Average $_{Ectg}$ Values ± One Standard Deviation for the Various Battery Technologies, as Shown on a per Watt-Hour Basis (same information as in FIGURE 3, except on a per watt-hour basis).

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

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

In summary, the status of life-cycle energy data for battery production is as follows: updated material production data are needed, and data gaps should be filled. In addition, process descriptions and material and energy flow data are needed for battery manufacturing. More specifically, material production data for Ni, Al, steel, polypropylene, and nylon are complete, current, and of high quality. Although dated, the existing material production data for many other battery materials, such as Pb, PbO, Na, and S are adequate for battery production life-cycle estimations. Unfortunately, the PE_j (and ideally {B}j) values for materials used in advanced battery technologies, such as LiCoO2, Cd, â-alumina, mischmetal hydrides, and others, are either missing, dated, or of unknown quality. With the exception of PbA batteries, published life-cycle data on battery manufacturing and assembly processes are generally unavailable, though some non-quantitative descriptions of process chains and flows have been published, as discussed in Section 3.2. This renders the manufacturing energy and emissions values reported herein as place holders and approximate. It is also evident in Table 2 that comparatively little life-cycle data are available on making batteries from recycled materials, and the data that do exist is poorly documented. Given the significant benefits estimated above for E_{mp} using recycled materials, more complete and better documented data are needed for material production from recycled materials.

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

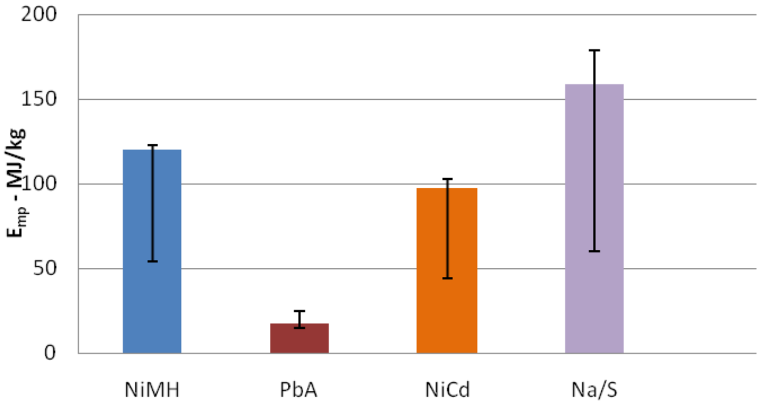

Figure 5. Estimated E_{mp} (MJ/kg) for Various Batteries from Virgin Materials (including range information)

3.5. Emissions Analysis

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

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

Table 12. Air, Water, and Solid Wastes for Cradle-to-Gate Battery Production (g/kg of Battery, Unless Otherwise Stated).

Technology	**VOC**	**CO**	**NOx**	**PM**	**SOx**	**CH^4**	**N^2O**	CO_2	**Water**	**Air**	**Reference**
g/kg								**kg/kg**	**mg/kg**		
NiMH	0.11 1.3	0.34 4.5	1.31 27	0.79 2.8	1.06 263	1.33 22.7	0.04 0.19	1.02 14.8	60 g Al, Ni, Co, etc., 18b – heavy metals	to air/water/solid 100b – heavy metals	Rantik 1999[a] Gaines et al. 2002
			19		14			15			Ishihara et al. 1999
	0.7	2.1	8.7	14.0	19.2	11.1	0.11	8.3			GREET 2.7
	0.9	3.9	11.4	18.9	20.5	15.3	0.1	10.3			Rydh and Sanden 2005[c]
	1.8	7.5	21.8	36.1	38.9	29.3	0.3	19.5			Rydh and Sanden 2005[c]
Average	1.2	4.5	17.6	18.0	71.1	19.6	0.2	13.6			
PbA	0.11	0.31	1.13	1.67	2.29	1.64	0.02	1.1	4.8 – Pb	1.2 – Pb	Rantik 1999[a]
	2.2	1.3	7.9	.8	10.3	.002	0.006	1.1	97 – heavy metals	118 – heavy metals	Kertes 1996
			5.8		5.3			5.1			Ishihara et al. 1999
	0.57	1.65	6.8	11.0	14.9	8.7	.09	6.4			GREET 2.7
	0.2	0.6	1.5	1.3	2.0	3.0	0.02	1.4			Hittman Associates 1980
	0.2	0.7	2.1	3.5	3.7	2.9	0.0	1.9			Rydh and Sanden 2005[c]
	0.3	1.2	3.5	5.7	6.0	4.6	0.0	3.1			Rydh and Sanden 2005[c]
Average	0.7	1.1	4.6	4.5	7.0	3.8	0.0	3.2			
NiCd									60 – Cd, Co, Ni	40 – Cd, Co, Ni	Rantik 1999[a]
	5.9	5.4	40	5.2	265	0.001	0.015	6.2	30 – heavy metals	740 – heavy metals	Kertes 1996

Table 12. (Continued)

Technology	VOC	CO	NOx	PM	SOx	CH^4	N^{2}O	CO$_2$	Water	Air	Reference
			g/kg					kg/kg	mg/kg		
	0.6	1.9	8.6	11.3	16.9	9.5	0.1	7.3			Ishihara et al. 1999
	0.7	2.8	8.1	13.4	14.5	10.9	0.1	7.3			Rydh and Sanden 2005[c]
	0.9	3.8	11.1	18.3	19.8	14.9	0.1	9.9			Rydh and Sanden 2005[c]
Average	2.0	3.5	17.0	12.1	79.0	8.8	0.1	7.7			
Na/S	1.67	5.4	20.5	25.6	38.0	27.3	0.2	18.2			Hittman et al. 1980
	1.1	4.4	13.0	21.4	23.4	17.3	0.2	11.6			Rydh and Sanden 2005[c]
	1.2	4.9	14.6	24.2	26.5	19.6	0.2	13.2			Rydh and Sanden 2005 [c]
Average	1.3	4.9	16.0	23.7	29.3	21.4	0.2	14.3			
Li-ion			22.5		17.5			18.2			Ishihara et al. 1999
	0.6	1.8	7.6	17.3	16.7	9.7	0.1	7.2			GREET 2.7
Average	1.1 1.7 0.9	4.3 6.4 3.0	13.3 20.0 14.5	21.9 32.9 19.6	24.9 37.4 19.7	17.6 26.5 13.7	0.2 0.2 0.1	12.1 18.1 12.5			Rydh and Sanden 2005c Rydh and Sanden 2005c

[a] Does not include battery material production.

[b] Solely from Ni production; assumed battery is 25% Ni.

[c] Used the average of their total energy values cited in Table 2.

Table 13. Emissions to Air, Water, and Solids for Battery Recycling (g/kg Battery, Unless Otherwise Stated).

Technology	**VOC**	**CO**	**NOx**	**PM**	**SOx**	**CH^4**	**N^2O**	CO_2	**Water**	**Air**	**Reference**
g/kg				**kg/kg**					**mg/kg**		
NiMH	0.107	0.386	1.390	2.047	2.786	1.619	0.016	1.234	0.24 kg slag and 30 g toxics – solid		Rantik 1999
PbA	0.425	1.762	1.966	0.520	0.522	0.768	0.025	0.604	< 0.1 Sb, Hg, Ni, Pb, etc	5.0 – Pb, Cd, Cu, Zn, As	Rantik 1999
NiCd	0.111	0.429	3.1	0.386	2.71	0.492	0.014	0.378	< 0.1– Cd, Ni	1.0 – Cd, Ni	Rantik 1999

3.5.1. Carbon Dioxide Emissions

Tables 12 and 13 list all relevant combustion gases individually. We do not report aggregate GHG emissions. The interested reader can convert the CO_2, N_2O, and CH_4 listed in the tables to GHG $_{(}CO_{2)eq}$ by using well-established equivalency factors. In general, GHG emissions per kilogram of battery are at most a few percent greater than direct CO_2 emissions.

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

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

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

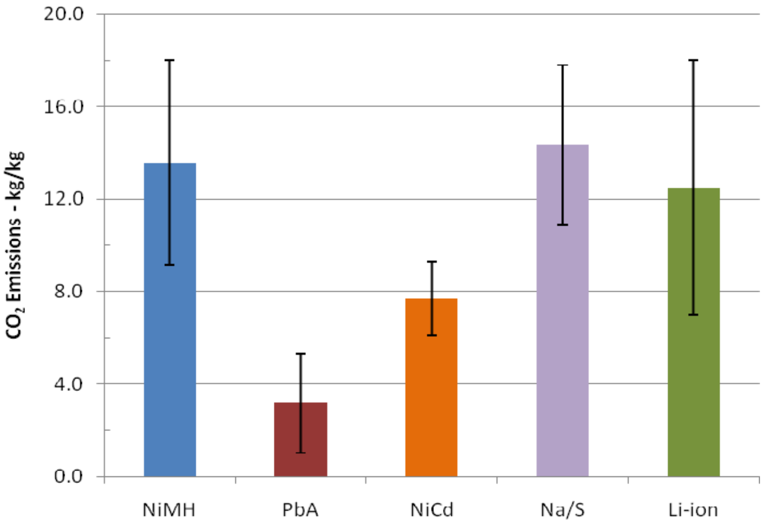

Figure 6. Average CTG CO_2 Emissions ± One Standard Deviation for the Production of a kg of Various Battery Technologies.

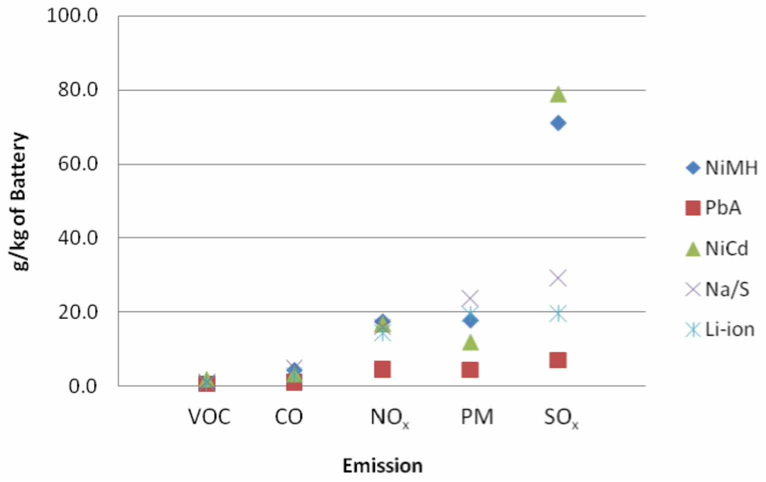

Figure 7. Average Criteria Pollutant Emissions (grams) per Kilogram of Battery for Five Batteries.

3.5.2. Criteria Pollutants

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

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

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

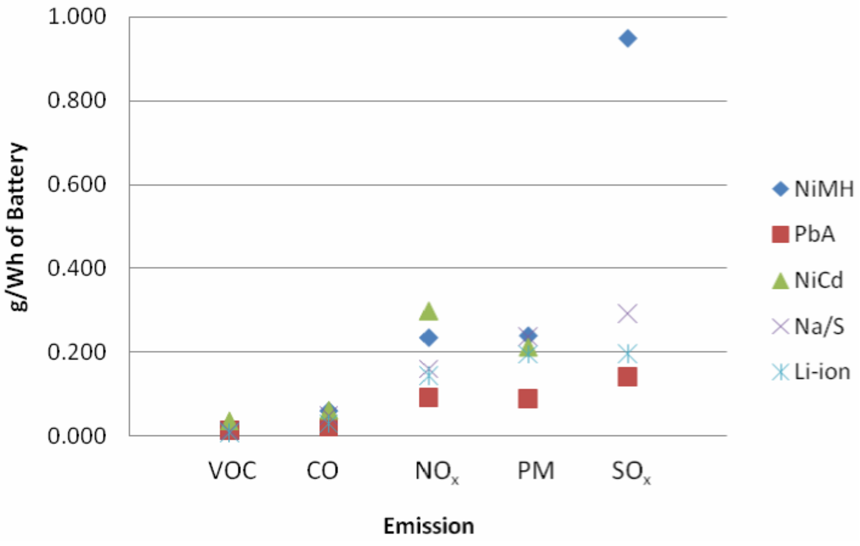

FIGURE 8 Average Criteria Pollutant Emissions (grams) per Wh of Battery Capacity for Five Batteries.

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

3.5.3. Other Emissions

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

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

3.6. Use of Results in Product Life Cycles

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

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

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

In short, based on the demand, the $_{\mathrm{LCEbat}}$ for the application is the number of batteries needed times the $_{\mathrm{Ectg.}}$ However, the $_{\mathrm{LCEbat}}$ is just one component of a product system’s life-cycle energy. Suppose that a battery electric vehicle is being considered. The total life cycle energy for the vehicle is:

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

where vh denotes vehicle, mp means total vehicle material production, op stands for vehicle operation, and “other” denotes terms like maintenance repair and end-of-life, which are usually quite small. As pointed out above, $_{\mathrm{LCEbat}}$ is a component of $_{\mathrm{LCEmp}}$ + $_{\mathrm{LCEassm.}}$ For LCE$_{\mathrm{o}}$p, in magnitude the largest term in equation (5), we write:

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

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

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

4. CONCLUSION

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

Based on existing material production data for battery materials, estimates of battery material production were made and found to be within the range of existing data. However, there is considerable variance in the existing data. Due to a lack of material production data, the same estimates could not be done for

Li-ion batteries. Better estimates of battery material production are also needed for some materials in NiMH and NiCd batteries.

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

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

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APPENDIX

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

Battery	Note	E_{mp} Virgin	E_{rcycl}	E_{mnf}	E_{ctg}	Specific Energy	Reference
NiMH		1.45	0.27	0.14	1.59		Ishihara et al. (website)
					3.97[b]	59	Ishihara et al. 1999
	AB_2				3.25	75.8	Gaines et al. 2002
					2.57[d]		Gaines et al. 2002
	AB_5				4.13		Gaines et al. 2002
		0.75				75.8	Gaines and Singh 1995
		1.6	0.6[c]	2.1		35–55	Rydh and Sanden 2005
				0.17[a]		75–95	Rantik 1999
							GREET 2.7
PbA		0.53	0.19	0.27	0.87		Ishihara et al. (website)
					1.81[b]		Ishihara et al. 1999
		0.49				50	Gaines and Singh 1995
		0.77	0.45[c]	0.42		20–32	Rydh and Sanden 2005
				0.37[a]		35–55	Rantik 1999
							Kertes 1996
		0.36		0.18	0.54	50	Hittman Associates 1980
NiCd		1.81					Gaines and Singh 1995
							Kertes 1996
		2.0	1.0[c]	2.1		22–30	Rydh and Sanden 2005
Na/S		0.60				100	Gaines and Singh 1995
		1.72		0.54	2.26	104	Hittman Associates 1980
		0.8	0.29	0.6		103–116	Rydh and Sanden 2005
Li-ion	NCA-G	1.16	0.05	0.32	1.50		Ishihara et al. (website)
	LMO-G	1.15	0.02	0.30	1.46		Ishihara et al. (website)

Table A-1. (Continued)

Battery	Note	E_{mp} Virgin	E_{rcycl}	E_{mnf}	E_{ctg}	Specific Energy	Reference
	$LiNiO_2$				1.49–2.23[b]	100–150	Ishihara et al. 1999
	NCA-G	0.67	0.31[c]	1.2		80–120	Rydh and Sanden 2005
		1.13		0.92	2.05	100[e]	GREET 2.7
					2.22	100[e]	Umicore Slide/Virgin
	NCA-G						Materials
					0.63	1 00[e]	Umicore Slide/Recycled
	NCA-G						Materials

* See Section 3.1.4 for Li-ion nomenclature; E_{rcycl} denotes energy to recycle batteries.

[a] Computed from cited values of production energy per kilogram and median specific energy.

[b] Appears to be a combination of material production and battery production using "hybrid analysis."

[c] Reported as material production energy using recycled materials.

[d] Same as above, except that recycled Ni is used.

[e] These values are assumed.

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Chapter 5

BATTERIES FOR VEHICULAR APPLICATIONS

Venkat Srinivasan

ABSTRACT

This paper will describe battery technology as it relates to use in vehicular applications, including hybrid-electric vehicles (HEV), electric vehicles (EV), and plug-inhybrid-electric vehicles (PHEV). The present status of rechargeable batteries, the requirements for each application, and the scientific stumbling blocks that stop batteries from being commercialized for these applications will be discussed. Focus will be on the class of batteries referred to as lithium batteries and the various chemistries that are the most promising for these applications. While Li-ion is expected in HEVs in the very near future, use in PHEVs are expected to be more gradual and dependent on solving the life, safety, and cost challenges. Finally, batteries for EVs remain problematic because of the range and charging-time issues.

INTRODUCTION TO BATTERIES

Several electrical energy storage and conversion devices have been considered for use in vehicle applications. These are illustrated in Figure 1 in the form of a Ragone plot, wherein the abscissa is specific power (which can be thought of as acceleration in a vehicle) and the ordinate is specific energy (or range in an EV). The graph shows these quantities for various batteries, electrochemical capacitors, and fuel cells. Note that this plot shows specific energy and power on a cell level for batteries made for many different applications, from consumer electronic to vehicles. An additional derating will need to be applied when analysis is done on the pack level. The figure shows that lithium-ion (Li-ion) batteries are superior to nickel metal hydride (Ni-MH) batteries for all three applications from a performance standpoint. The figure also shows that no battery system has the ability to provide energy close to what is possible with gasoline (Internal combustion, or IC-Engine). Finally, the figure suggests that batteries are superior to capacitors for applications where the time of discharge is greater than the order of seconds.

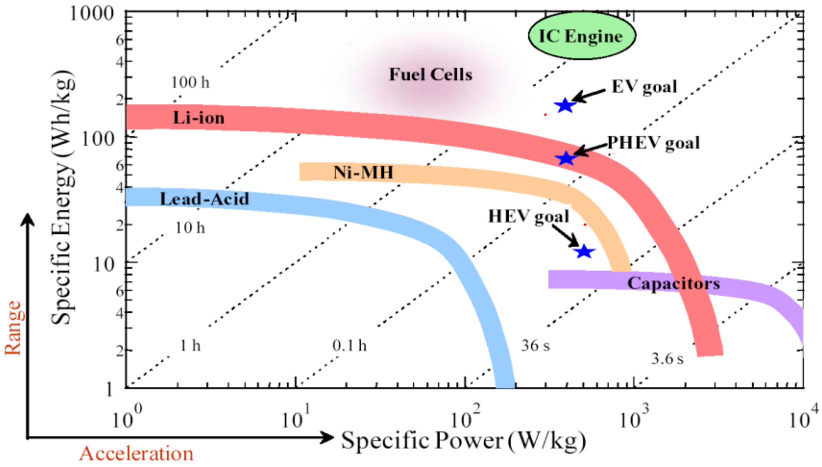
The United States Advanced Battery Consortium (USABC) has set the requirements needed for batteries to be used in EV, PHEV, and HEV application.[1] These requirements cover a wide range of issues and include energy and power. In order to compare the requirements to the performance of these devices illustrated in Figure 1, a few assumptions have to be made, which are done here for the sake of simplicity. While the USABC requirements for power represent a peak power for a 10s charge/discharge, the systems in Figure 1 show average power. Similarly, the USABC requirements show energy as an *available* energy, which typically is less than the total energy of the cell. For a HEV, available energy can be as little as 20-30% of the total energy, while for an EV or PHEV, this could be as large as 70-80%.

Despite these differences, a superposition of the USABC requirements onto Figure 1 is illustrative. The figure shows that while Li-ion batteries can easily satisfy HEV requirements, the energy is much smaller than the requirements for EVs. Similarly, the energy needs of a 40 mile PHEV (96 Wh/kg available energy) could be achieved by a high-energy Li-ion cell (similar to the batteries used in the Tesla Roadster).[a]

However, while the plot captures the performance map of various batteries, other criteria need to be considered, including cost, cycle and calendar life, and safety. Moreover, these factors are connected to each other. For example, while PHEVs *appear* possible with Li-ion batteries today from an energy standpoint, this would require the use of batteries that are not made for EV applications and that are cycled over a very wide state of charge (SOC) range, thereby limiting cycle life. One could increase the life by limiting the extent to which these batteries are charged, however, this would limit the energy of the cell, and thereby increase the cost, and the volume and weight of the final battery. Indeed, an analysis of presently-available EV batteries with characteristics that enhance cycle/calendar life suggests that meeting the energy requirements for a 40 mile PHEV is difficult. Finally, the importance of each of these factors changes from application to application. Therefore, while peak power could be an important criterion for a HEV, energy density would be a critical parameter in an EV. Some criteria, like cost and safety, remain challenges in all applications.

While complicated, the interplay between these various factors is tractable and suggests that Li-ion batteries remain the most promising candidate for use in vehicular applications. The three main reasons for this conclusion are the higher energy, higher power, and the potential for lower cost of Li-ion batteries when compared to Ni-MH batteries. This conclusion has been the reason why significant research efforts have been directed toward Li-ion batteries. In this paper, we will explore the limitations that Li-ion batteries face when used in each of the three applications (HEV, EV, and PHEV), the underlying technical challenges behind the limitations, and the approach taken by researchers the world over to address these limitations. We begin with a brief tutorial on batteries.

Batteries typically consist of two electrodes, an anode and a cathode with a separator between them to prevent shorting. The cell is filled with electrolyte. Figure 2 illustrates a typical Li-ion cell sandwich consisting of a graphite anode and a lithium cobalt oxide cathode ($LiCoO_2$).



Source: Product data sheets

Figure 1. Ragone plot (specific power density in W/kg vs. specific energy density in Wh/kg) of various electrochemical energy storage and conversion devices.

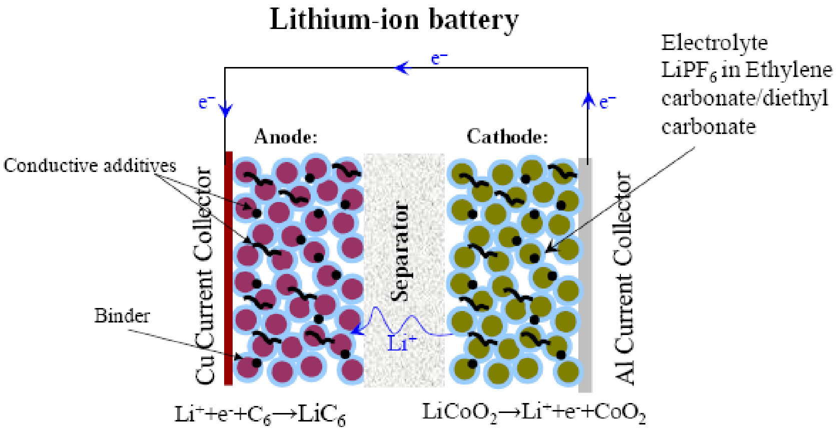


Figure 2. Schematic of a typical Li-ion cell.

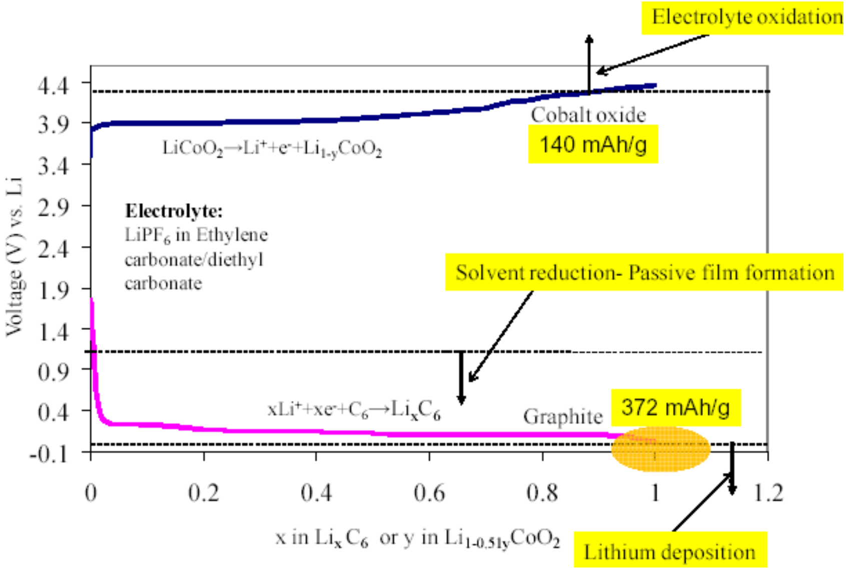


Figure 3. Steady state charge curve of a Li-ion cell consisting of a graphite anode and a $LiCoO_2$ cathode. The graph shows the half cell potentials and the thermodynamics potentials for various side reactions.

The electrodes consist of active materials bound together with an electronically insulating binder and conductive additives. Each electrode is pasted onto current collectors. During charge, Li is removed from the cathode (or positive electrode), transferred through the separator via the electrolyte and is inserted into the anode. The reverse occurs on discharge. The difference in voltage of the cathode and the voltage of the anode is the cell voltage. The amount of Li that is stored in each of these materials is related to the capacity (often given in mAh/g). The product of the voltage and the capacity is the energy. How quickly the Li is transferred from one electrode to the other (or how quickly the energy is removed) is related to the power. More details on batteries can be found in references 2, 3, 4, and 5.

Figure 3 shows the typical steady-state charge of the anode and cathode of a Li-ion cell with a graphite anode and a LiCoO2 cathode in an organic electrolyte consisting of a Li salt (lithium hexafluoro phosphate, LiPF6) in a solvent (e.g., ethylene carbonate and diethyl carbonate). This is the battery used in laptops and cell phones. The voltage of each electrode is represented with respect to a Li-metal reference electrode. As the Li is removed from the cathode, its potential increases, while the potential of the anode decreases with insertion of Li. The process of Li moving in and out of the electrodes is referred to as intercalation/deintercalation. The voltage of the battery is the difference in voltage of the cathode and the anode, which increases as charge proceeds. The abscissa represents how much Li is stored in the cell, while the ordinate shows at what voltage the Li is inserted/removed from the materials. In order to increase the energy of the battery three avenues can be pursued, namely (i) increase the voltage of the cathode, (ii) decrease the voltage of the anode, and (iii) increase the capacity of the cell. However, the thermodynamics of electrochemical reactions other than the intercalation of Li (referred to as side reactions) limit these quantities.

The three side reactions worth mentioning in this plot are the oxidation of the solvent that occurs above ~ 4.2 V *vs.* Li, Li-metal deposition that occurs below 0.0 V *vs.* Li, and solvent reduction that occurs below ~1 V *vs.* Li. These three reactions not only limit the energy of the cell, they are also implicated in the life and safety problems associated with Li-ion batteries. Staying within the voltage window allows these problems to be minimized, at the loss of energy. The tradeoffs that are needed to balance these various parameters are captured by Figure 3.

Innovation in Li-ion batteries can occur in two ways, (i) *via* engineering advances that reduce, *e.g.*, the thickness of the separator and/or (ii) *via* innovation in the materials used as the active material. For example, the chemistry used in present-day cell phone and laptop batteries (LiCoO2/graphite) has a theoretical energy density of ~360 Wh/kg (this accounts for only the weight of the active material and not the weights of the other components in the cell such as the current collectors, electrolyte, binders, and cell packaging). The practical energy density of a packaged 18650 cell is ~1 90 Wh/kg. Fifteen years ago, in the early days of Li-ion, this number was ~90 Wh/kg, using the same material sets.[6] In other words, over the last 15 years, engineering advances have resulted in a doubling of the energy density of Li-ion batteries. It is expected that in the future, improvements in performance will occur by moving to new higher energy materials.

Fortunately, it has been observed that Li can intercalate into many different anode and cathode materials. At present, three classes of cathodes, four classes of anodes, and four classes of electrolytes are being considered for use in Li-ion cells. Depending on the combination of the anode, cathode, and electrolyte, one can have a completely new battery with changes to the energy, power, life, safety characteristics, low temperature performance, *etc.* These classes are illustrated in Figure 4 for the three components of the battery.

Each of these classes is a collection of numerous specific materials with their own different characteristics. For example, the LiCoO2 electrode used today falls under the class of layered materials. Its capacity is 140 mAh/g. A new cathode emerging in the market is LiNi0.8Co0.15Al0.05O2 (NCA), also a layered material but with a capacity of 185 mAh/g. This increase in capacity means a significant increase in the energy of the cell, reiterating that many different materials combinations can be used to tune the battery to suit the application for which it is used. This behavior of Li batteries makes it very different from other classes of batteries, for example, the lead-acid system where the material set is fixed. It also adds additional degrees of freedom for researchers to find new materials and in effect make a new battery.

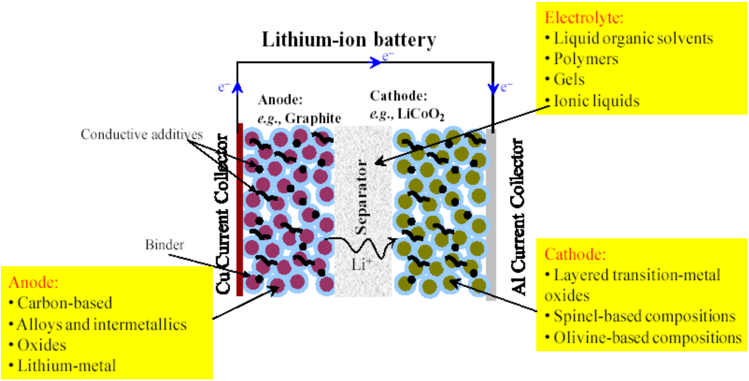


Figure 4. Schematic of a Li-ion cell with the various anode, cathode, and electrolytes that are presently being considered. Changing the combination results in changes to the energy, power, safety, life, and cost.

One issue worth mentioning is the concept of capacity balancing. Today's Li-ion batteries are typically referred to as cathode limited. In other words, the capacity of the cathode (140 mAh/g for LiCoO2) limits the capacity of the battery, as it is smaller than the capacity of the anode (372 mAh/g for graphite). What this means is that the cathode has a significantly higher impact compared to the anode in increasing the energy of the cell. A quick calculation shows that an order of magnitude increase in the anode capacity increases the capacity of the cell by only 35% (one would also need to see at what voltage this new anode operates in order to estimate the improvement in energy).

While the flexibility of Li batteries provides the means to tune the battery's characteristics, it appears that no ideal combination has been found that satisfies the needs of vehicular applications. We now briefly look at the three applications, the status of batteries in these applications, and the research that is being pursued.

BATTERIES FOR HEVS

Over the last 5 years enormous progress has been made in using Li-ion batteries for HEV applications. The most studied system typically consists of the NCA cathode with a graphite anode. With continuous improvements this system has overcome many of the limitations and has come closer to satisfying a majority of the requirements set out by the USABC. In particular, the calendar life of this chemistry has been projected to be greater than 15 years based on accelerated testing, when the SOC of the battery is controlled carefully. This promising development provides hope for use in vehicles.

Despite these advances, three main barriers remain before commercialization: (i) cost, (ii) low-temperature operation and (iii) safety.[7] It has been shown that a large proportion of the cost of HEV batteries is due to the separator (25%) and the electrolyte (17%) (note that in a HEV cell, where the electrodes are thin, there is more separator area for the same size compared to an EV battery).[8] Therefore, efforts to make low-cost separators would help with the cost reduction in the cell. An ability to make low-cost separators thinner, without compromising safety, would enhance power, and minimize cost simultaneously. In addition, lower cost electrolytes and cathodes would also help in decreasing the cost of the battery. Finally, as the important metric for a HEV is $/kW of power, a new chemistry that promises higher power at the same cost per cell would result in a lower pack cost.

When operating Li-ion batteries at low temperatures (less than 0ºC), it has been seen that the power capability decreases significantly because of increased resistance in the cell. It is thought that the increased resistance is caused by the reduction in the kinetic rate constants of the electrochemical charge-transfer reaction.[9] This has implications during regeneration where the anode in the Li-ion cell is accepting Li at high rates. It has been observed that instead of intercalating into the graphite structure, the Li plates on the surface. The Li metal then reacts with the electrolyte and gets consumed, leading to capacity fade. While it is known that the choice of the solvent can have a significant impact on the low-temperature performance, these special solvents come at an additional cost. An alternative technique is to use an anode that allows the lowering of the impedance without causing Li plating. This can be achieved if the voltage of the anode is much higher than the voltage for Li-plating, allowing a bigger window before plating occurs. Lithium titanate (Li4Ti5O12) is a candidate that allows this feature because its voltage is 1.5 V *vs.* Li. Companies such as Toshiba, Enerdel, and Altair Nano are pursuing this concept to allow low- temperature operation and fast-charge capability (in addition to possible safety and life enhancements). However, the high anode voltage results in a low cell voltage and therefore decreases the energy of the battery.

It also should be noted that if the HEV is designed so that the battery is not used when cold but instead is allowed to warm up using the IC engine, then the problem of low-temperature operation could be circumvented. At present, it appears that the HEVs of the near future will be using this strategy. A pure EV would be prone to have a problem from this low-temperature limitation because no means exist to heat the battery when it is not plugged into an electrical outlet. Here, again, the problem could be solved by not allowing regeneration until the battery warms, and by using the battery to power the car (albeit at lower acceleration) until it self-heats.

The last limitation of Li-ion batteries is the safety of the pack, highlighted by the recent incidents involving fires of consumer-electronics batteries. The main cause of safety limitations in Li-ion cells can be characterized by the three stages in which thermal runaway occurs.[10] In stage 1, an unexpected failure occurs in the cell, *e.g.,* internal shorting (*e.g.,* due to metal particles) or malfunction of the overcharge protection system. This results in the temperature of the cell increasing to around 125°C, where a reaction that involves decomposition of a passive layer on the anode (called the solid electrolyte interphase layer or SEI) occurs; an exothermic reaction that increases the temperature further. As the temperature increases to above

180°C, in some cathodes, the oxygen from the lattice is released, resulting in a rapid increase in heat in a short time. This chain reaction results in the smoke and the fires that have been observed in Li batteries.

One can prevent/retard these reactions in different ways. For example, using a cathode that does not release oxygen could help in suppressing the final exothermic step. Lithium iron phosphate is one such cathode that is being pursued by various companies, notably, A123 systems and Phostech. A second approach is to prevent the cell from approaching these temperatures by preventing the decomposition of the SEI. Lithium titanate is an example of an anode where no SEI forms and so it has been argued that this makes the battery safer. Finally, research efforts are underway to develop overcharge protection mechanisms, such as redox shuttles, electroactive polymers, and high puncture-strength separators to prevent internal short circuits. These ideas are aimed at preventing the cell from reaching the temperatures where the anode reactions occur. Finally, electrolytes that are not flammable and nonvolatile (*e.g.,* ionic liquids) help minimize the impact of these incidents even if the reactions do occur.

To summarize, three problems prevent the widespread commercialization of Li-ion batteries for HEVs today, cost, low-temperature operation, and safety. However, in the short-term, various engineering solutions can be adopted that can prevent the latter two. With cost being a highly socio-economic factor, it is thought that HEVs with Li- ion will start reaching the marketplace within the next few years.

BATTERIES FOR EVS

We will now examine the use of Li-ion batteries for EV applications. As was pointed out previously, Figure 1 suggests that the energy density of Li-ion batteries is not sufficient for use in present-day cars to provide the necessary range to make them commercially viable. A typical rule-of-thumb is that a sedan can go 1 mile on 300 Wh of battery. In other words, a car with 300 mile range requires a 90 kWh pack that can fit in the vehicle with little impact to passenger and luggage space. Presently available EV batteries have a specific energy of ~1 10 Wh/kg and 160 Wh/l,[11] suggesting that the 90 kWh battery will weigh 1800 lbs and have a volume of 148 gallons; far too large for existing vehicles. These energy numbers are on a pack level and are therefore smaller than those on a cell level. Further, note that these numbers are not meant to be precise, rather they are estimates to illustrate the challenges.

Arguments could be made that one may not need a 300-mile-range vehicle, that one could drive more than 1 mile with 300 Wh (for example, *via* the use of lightweight materials and better body design), and that one could enhance the specific energy on the pack level using lightweight battery packaging.[b] All these would help make EVs a reality. However, the cost of such a vehicle would still remain large, and, arguably, prohibitive. For example, the battery pack in the Tesla Roadster is reported to be $25,000. The fact that the Tesla batteries are made for consumer electronic applications, where the cost of batteries is considerably lower than that for vehicles, highlights the magnitude of the problem. Similar to HEVs, the important quantity is the $/kWh of the battery (a more comprehensive metric would be $/kWh/year or a lifetime cost on an energy basis[c]). Therefore, a higher energy chemistry could be a route to decreasing the cost of these batteries. Three ideas that are being pursued are discussed here.

As pointed out before, the capacity of cathodes used in consumer electronic batteries are limited by the solvent oxidation reaction that occurs at ~4.2 V *vs.* Li. At these limits, only ~50% of the lithium is removed from the lattice of the cathode. Tremendous improvements could be made if the extra lithium can be accessed. Efforts are underway to find new electrolytes that can be used in high-voltage cathodes. However, as of today, there appears to be no electrolyte that shows promise in increasing the voltage significantly. An interesting recent advancement has been in altering the surface of the cathode in order to modify the interface where reaction occurs. For example, it has been shown that coating the cathode with a layer of aluminum phosphate (AlPO4)[12] allows the potential to be pushed to higher values, thereby increasing the capacity and the energy, with little loss in capacity. This modification of the interface allows us to think of new ways to enhance the energy of the cell while maintaining cycle life and safety.

The second possibility is to change the anode to enhance the energy of the cell. Two options are being pursued in this area, (i) the use of anodes that alloy with Li, such as silicon and (ii) the use of Li metal. In area one, anodes, such have silicon, are attractive because they have high capacity (~3700 mAh/g) when compared to graphite (372 mAh/g).[13] Despite having a higher voltage compared to graphite (0.5 V *vs.* 0.1 V), the use of Si results in an increase in energy density by ~25-35%. However, several problems prevent alloys from being commercialized including a large volume change (~270% for silicon) with cycling that results in particle cracking/isolation, a large 1st cycle loss in capacity that results in Li being consumed to make a passive layer and not being active to provide capacity, and a continuous consumption of Li from cycle to cycle that limits the cycle life.[14] Several approaches are being pursued to alleviate these limitations.

Two that are worth noting are the use of what is termed "active-inactive matrix" where the active component (Si or Sn) is embedded in an inactive matrix (*e.g.,* carbon),[15] and the use of novel structures to accommodate the volume change. In the first approach, the carbon allows the expansion of the alloy without particle cracking. However, the added weight and volume of the inactive component limits the capacity of these anodes to ~1 200 mAh/g. This concept is used in the Nexilion cell introduced by Sony Corporation. In the second concept approach, micron-sized silicon pillars that reversibly cycle with high capacity are used.[16] A nano-sized analog of this concept was recently reported by a group at Stanford University.[17] While interesting, these structures require expensive and slow processing.

While these two approaches show promise in accommodating the volume change, efforts need to be made to reduce the 1st cycle capacity loss (which scales with surface area) and the cycle-to-cycle loss of Li. Use of "*in situ* SEI-formers" like the SLMP powder marketed by FMC Corporation could help with the former.[18] The use of additives could help with the latter.

In area two, using Li metal as the anode brings the promise of a large capacity (3800 mAh/g) at a voltage of 0.0 V, thereby increasing the energy of the cell. Lithium metal has been used in primary Li batteries for decades, however, its use in secondary batteries have not been successful because of problems during charging. During charge, Li plates on the anode and, similar to plating of other metals like zinc, does not plate uniformly. Instead, dendrites of Li grow on the surface and, with time, penetrate the separator and short the cathode. In addition, dendrites break and isolate Li resulting in capacity fade.

There have been numerous efforts over the decade to stop the dendrites from growing by placing the anode against a hard surface, such as a solid polymer electrolyte. It has been hypothesized that the hard surface of the polymer would prevent the dendrites from penetrating. However, it has been observed that as the stiffness of the polymer increases, its conductivity decreases, thereby limiting the power capability of the cell. This interplay between conductivity and stiffness has resulted in the inability to effectively prevent dendrites. The use of block copolymers, where one block is made of a stiff material like polystyrene, and the second block is made of a conducting phase, like polyethylene oxide, has allowed the decoupling of conductivity and stiffness.[19] However, as of today, these polymers operate at 80 C and have significantly lower conductivity compared to liquid electrolytes. The use of polymers for Li batteries is being pursued by companies such as Sion Power and Seeo Inc.

Another concept is the use of single-ion conducting glasses to isolate the Li. This concept has been explored by Polyplus Battery Company where it has been shown that the Li can be completely isolated to the point where it can be dipped in water. This concept is intriguing in that it enables the development of very high energy cells like Li-air and Li-sulfur. These glasses are not very conductive and are prone to defect formation. Advances in the behavior of solid polymers and ionic glasses could provide huge benefits in batteries.

While these approaches provide a pathway for enabling a higher energy cell that could allow the development of EVs, they fail to solve one other problem, namely, charging time. With typical battery charge times ranging from 3-8 hours, a change in lifestyle is needed when compared to using a gasoline car. While fast-charge batteries do exist (*e.g.*, Altair Nano and Toshiba), these come at the expense of energy. Further, infrastructure questions arise concerning the ability of the grid to handle a pure electricity-based transportation economy with fast-charge batteries. The issues of range and charging are circumvented with the use of a PHEV.

BATTERIES FOR PHEVS

The PHEV is an ideal compromise between the minimal fuel-saving advantage of the HEV and the range/charging-time issue of the EV. With the addition of the internal combustion engine for longer trips and a large battery pack to sustain 10-40 miles of equivalent electric range, the PHEV captures the best of both concepts. As suggested previously, the energy of the Li-ion cell is connected with the life and enhancing one typically lessens the other. While high energy Li-ion cells, similar to ones used in consumer electronic applications, could probably satisfy the range requirements for a 40 mile PHEV, the ability of these batteries to last 15 years is highly questionable. Typical EV batteries today do not appear to posses the energy needed for a 40 mile range. However, recent reports suggest that battery manufacturers are increasing moving to lightweight packaging that should allow the specific energy to increase. In addition, presently-available batteries should be sufficient to satisfy the energy requirements of PHEVs that have a lesser EV range (*e.g.*, 20 miles). However, two problems still need addressing, namely, cost, and cycle/calendar life.

Present cost estimates suggest that a 40-mile PHEV battery can cost upwards of $10,000.[d] While battery companies have been reporting cycle life of Li-ion cells in the 3000-5000 cycle range (approaching the USABC requirements), the more important question is the calendar life of these cells, particularly because these batteries may spend a considerable part of the time at high SOCs, the state where Li- ion batteries are most prone to exhibit capacity fade. Strategies are being pursued that involve decreasing the maximum SOC of the battery in order to enhance the life; however, these come at the expense of energy and therefore increase the cost of the pack. As of today, no clear data exists that shows the ability of Li-ion batteries to sustain 15 year life under PHEV conditions. This is expected to become available in the near future.

Concepts that involve increasing the energy of the battery *via* new materials, described in the EV section, will prove to be very effective in decreasing the cost (by decreasing the $/kWh). In addition, careful use of additives/coatings to modify the electrode/electrolyte interface in order to retard side reactions in the cell can help to enhance the life of the battery, without sacrificing energy. Finally, new materials that show inherent stability could also be useful in improving the life of these batteries.

We end the discussion of PHEVs by reminding the reader that safety remains a concern for all three applications and that the ideas to enhance safety suggested in the HEV section are applicable for PHEVs (and EVs).

FUTURE OF BATTERIES

The energy density of batteries has been increasing at the rate of ~5% per year over the last 15 years, well below the improvements that have been made in semiconductor devices (*e.g.,* Moore's law). The question arises as to how batteries will improve over the next 15 years. While difficult to predict, one can look at advances in the literature and project the impact these advances would have on energy. We choose to look at specific energy, although energy density is also important. This is summarized in Figure 5 where the specific energy is captured at the cell level. We split the plot into "low risk" where two advances are expected. One involves the move to a NCA-like cathode from $LiCoO_2$ (which is already underway) and the second involves the move to an active-inactive alloy (similar to the Nexilion cells, but with higher capacity). We then describe higher risk systems that involve moving to high-voltage-transitionmetal-oxide (TMO) cathodes and to alloy anodes that have much larger capacity. These are considered possible, if the concept of coatings work to enhance the capacity of cathodes without compromising safety and life and if alloys, like Si, prove to meet the cycle life requirements. While both these are far from certain, the literature results are encouraging. [12,20] Because of the uncertainty, we denote this as higher risk. These advances, if successful, would result in the doubling of the energy of present day batteries; a significant increase.

Next, we address the issue of the theoretical limit of the energy of batteries. While some use a periodic table to evaluate this number, we choose to highlight systems that are very far from reality, but have been alluded to in the literature. Three of these systems are listed in Figure 6 including zinc-air, lithium-sulfur and lithium-air. Note that the numbers in this figure are theoretical energies (that do not include any weights except that of the active material). The figure shows that batteries today are very far from achieving the theoretically maximum-possible energy. Efforts are underway both in the research community and in industry to examine these systems. For example, the Zinc-air technology is being pursued by ReVolt Technologies in Sweden and the Li-S cell is the focus of Sion Power. However, note that while the figure shows the theoretical specific energy, practical values are far below these quantities. For example, the target for Li-S cells is in the range of 350 Wh/kg; less than a doubling of presently-available systems. This shows the difficulty involved with these chemistries and the long-term nature of the research for them to be commercial.

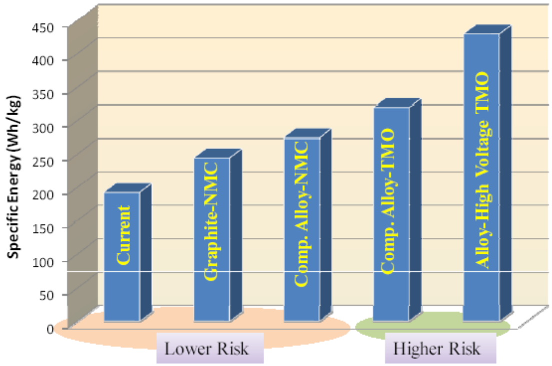


Figure 5. Projected increase in energy density (Wh/kg) of Li-ion cells on a cell level; NMC -LiNi1/3Co1/3Mn1/3O2, TMO - transition metal oxide. Based on Draft of FreedomCAR PHEV R&D Plan: http://www1.eere.energy.gov/vehiclesandfuels/features/phevplan.html.

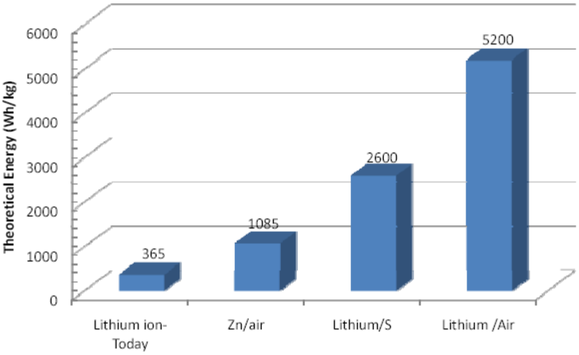


Figure 6. Theoretical specific energy (Wh/kg) of various electrochemical couples. All numbers are theoretical energy densities and accounts only for the weight of the active material.

Finally, we examine the need for non-Li-based systems for energy storage for vehicles. While systems are being researched (like magnesium and sodium), these appear further away from commercialization. Considering the wide variety of materials that Li can intercalate into, it appears that Li-based batteries (whether Li-ion or Li-metal) offer many opportunities for improvements that are worth pursuing. While it can be argued that being dependent on a single cathode or anode material (like being dependent on platinum in a fuel cell) would lead to resource limitations, one should note that with the wide material set for the anode and cathode for use in a Li-ion cell, one has opportunities to spread the risk among many different metals. The one common metal that is needed for all Li-based cells is Li. Back of the envelope calculations show that Li-metal limitations should not be an issue for at least the short to intermediate term. However, a comprehensive study is probably needed to ensure that this resource is not limited if widespread penetration of PHEVs and EV do occur.

CONCLUSIONS

Lithium-ion batteries offer many advantages that make them suitable for use in vehicular applications, including higher energy and power capability and, possibly, lower cost compared to Ni-MH cells. One significant advantage of the Li battery is that the chemistry (*i.e.*, materials for the anode, cathode, and electrolyte) are not fixed and a wide variety can be used, each of which can change the characteristics of the system. This provides battery researchers with additional degrees of freedom. However, with each choice, it has been observed that while some characteristics are improved, others prove lacking. No silver bullet has been found that can be considered an ideal Li chemistry.

While Li-ion is expected in HEVs in the very near future, use in PHEVs is expected to be more gradual and dependent on solving the life and cost challenges. Finally, batteries for pure EVs remain problematic because of the range and charging-time issue. A focus on higher energy systems would help decrease the $/kWh. Similarly, the use of coatings and additives will play a large role in enhancing life. Safety remains a big concern with Li batteries, highlighted by the recent incidents plaguing the consumer electronics market. Both engineering and materials approaches are being pursued to address this challenge. Safety will remain in the forefront of any discussion of battery-powered vehicles and much care and attention is needed to ensure that no incidents occur that undermine this concept.

The future of batteries remains very strong and one can be optimistic as to the advances that will occur in this class of energy storage devices. Considerable improvements can still be made to the concept of a Li-ion battery, both in terms of finding new materials and in alleviating the limitations of existing systems. Batteries exist that promise tremendous improvements compared to the ones presently available; however there are significant challenges in commercializing these systems. The key to enabling these systems to operate with high energy, long life, and good safety characteristics lies at the interface. Modification of the interface will play an increasing important role in batteries in the near future.

ACKNOWLEDGMENT

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End Notes

[a] Assuming a packaging factor of 0.7, a consumer electronics battery with energy of 180 Wh/kg has a pack-level energy density of 126 Wh/kg. A 76% SOC range of cycling results in this battery meeting the requirements. However, note that typical EV batteries have a much lower energy density (pack level of 110 Wh/kg) due to the life requirements.

[b] One can perform an optimistic calculation using a high-energy Li-ion cell of say 180 Wh/kg specific energy with a packaging factor of 0.8 resulting in a pack level specific energy of 144 Wh/kg. For a 200 mile vehicle, this would require 900 lbs of battery; a more manageable number.

[c] For a Tesla battery, which is a 56 kWh battery which would last, as reported, 5 years, the $/kWh/year is 90. The USABC longterm goal is $10/kWh/year (and 15 for the short-term) for EVs.

[d] USABC goal for available energy of a PHEV-40 is 11.6 kWh. Assuming a 70% range, this means that the total battery size would be 16.5 kWh. Assuming a cost of $1000/kWh for a PHEV cell, this would mean a total cost of $16,500 for the battery pack. While not well understood, the life of this battery *could* be 10-15 years. One could perform an alternate calculation: Assuming that one uses a consumer electronic battery with the same characteristics as the battery for a Tesla Roadster, a 40 mile PHEV would cost $5,000 (1/5th

the cost of the Tesla battery of total energy 11.2 kWh). Assuming, optimistically, that this battery lasts 5 years, this means a yearly cost of $1000 for the battery pack. Assuming that the battery is cycled 300 times in a year (for a total of 12,000 miles pure EV driving), the cost of electricity would be $270 at $0.08 per kWh. In other words, one would need $1270 per year to pay for the battery and the electricity per year. Assuming a 3 year battery life (arguably more realistic) increases this cost to $1935 per year. To drive the same miles in a gasoline car with 30 mpg mileage would require $1800 per year, assuming gasoline costs at $4.5 per gallon (costs in the San Francisco Bay Area as of June 2008). Both calculations allude to the need for creative financing options (*e.g.*, battery leasing) to offset the initial investment needed to buy a PHEV.

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