Congressional Research Service

Battery Manufacturing for Hybrid and Electric Vehicles: Policy Issues

Bill Canis
Specialist in Industrial Organization and Business

March 22, 2011

Congressional Research Service
7-5700
www.crs.gov
R41709

CRS Report for Congress
Prepared for Members and Committees of Congress

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.

Contents

Figures

Tables

Appendixes

Contacts

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.

Using the Internet to Learn About Electric Vehicles

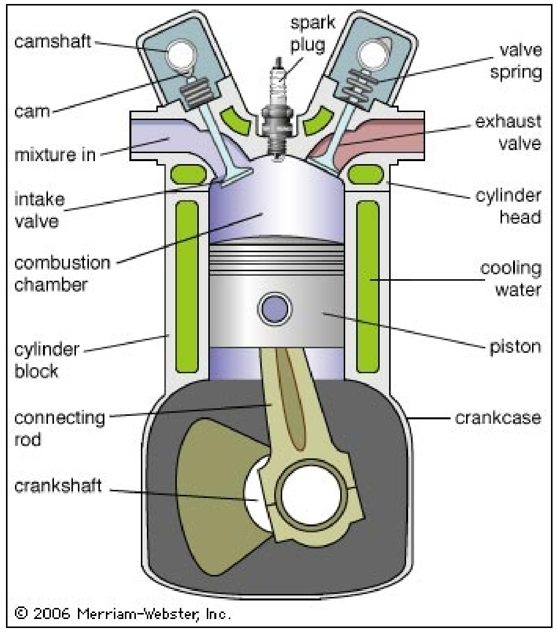
When you see this camera icon in a box in this report, it indicates an Internet video resource that will be helpful in understanding dimensions of the battery industry, such as how lithium is mined. The box will give a short summary of the contents of the video. Either click on the camera icon or paste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

[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.

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.

Figure 1. Major Parts of an Internal Combustion Engine



Source: Used with permission of the publisher. From *Merriam-Webster's Collegiate® Encyclopedia©2000* by Merriam-Webster, Inc. (http://www.Merriam-Webster.com).

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.

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]

[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.

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]

[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, click the following link, or copy or type it into a browser window: http://www.youtube.com/watch?v=4IgHj2Uim_0 (viewed on March 22, 2011).

Figure 2. The Lead-Acid Battery

Showing Internal Components

Source: Reprinted with permission from Exide Technologies.

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,

[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.

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]

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.

[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.

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 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.

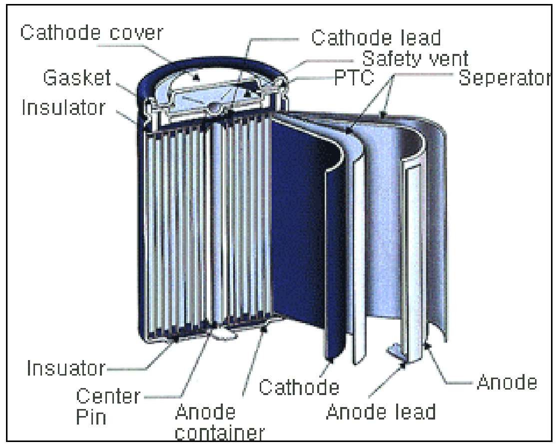
Li-ion battery cells can also be manufactured in rectangular shapes using gel as the electrolyte, and then encased in laminated film. Rectangular cells can be more efficient because their shape means more finished cells can be assembled in a battery pack, increasing the density of the battery.[21] The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

[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.

- *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.

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



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.

- *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]

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**.

[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.

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 Statues 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

[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.

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]

[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.

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.

[34] "Chile's Underground Riches," *World News Network*. To access the video on how lithium is mined in Chile, click the following link, or copy or type it 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.

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.

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]

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

[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.

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

[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.

> 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.

---

[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.

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]

[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-cell-manufacturing-part-3.html.

[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.

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**.

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]

---

[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.gov/news/documents/1_Million_Electric_Vehicle_Report_Final.pdf.

[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.

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 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]

[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,
(continued...)

- 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]

(...continued)

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.

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

[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.

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.

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).

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

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.

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.

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.

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]

---

[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
(continued...)

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]

(...continued)

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,
(continued...)

- *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]

(...continued)

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.

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.

---

[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.

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 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 UltraBattery (lead-acid battery with a carbon supercapacitor combination) for micro and mild hybrid applications.

Recovery Act Awards for Electric Drive Vehicle Battery and Component Manufacturing Initiative

Applicant	DOE Award (in Millions of Dollars)	Project Locations	Technology
Advanced Battery Supplier Manufacturing Facilities			
Celgard, LLC, a subsidiary of Polypore	$49.2	Charlotte, NC Aiken, SC	Production of polymer separator material for lithium-ion batteries.
Toda America, Inc.	$35	Goose Creek, SC	Production of nickel-cobalt-metal cathode material for lithium-ion batteries.
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 hexafluorophosphate (LiPF6)) for lithium-ion batteries.
BASF Catalysts, LLC	$24.6	Elyria, OH	Production of nickel-cobalt-metal cathode material for lithium-ion 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

Figure B-1. Overview of the GM Volt

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.

Appendix C. Current and Planned Hybrid and Electric Vehicles in the U. S. Market

Hybrid Electric Vehicles (HEV):

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)
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

Extended Range Electric Vehicles (EREV):

2010 Chevy Volt Extended Range EV

Plug-in Hybrid Vehicles (PHEV):

2010 Fisker Karma S Plug-in Hybrid
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.

Author Contact Information

Bill Canis
Specialist in Industrial Organization and Business
bcanis@crs.loc.gov, 7-1568