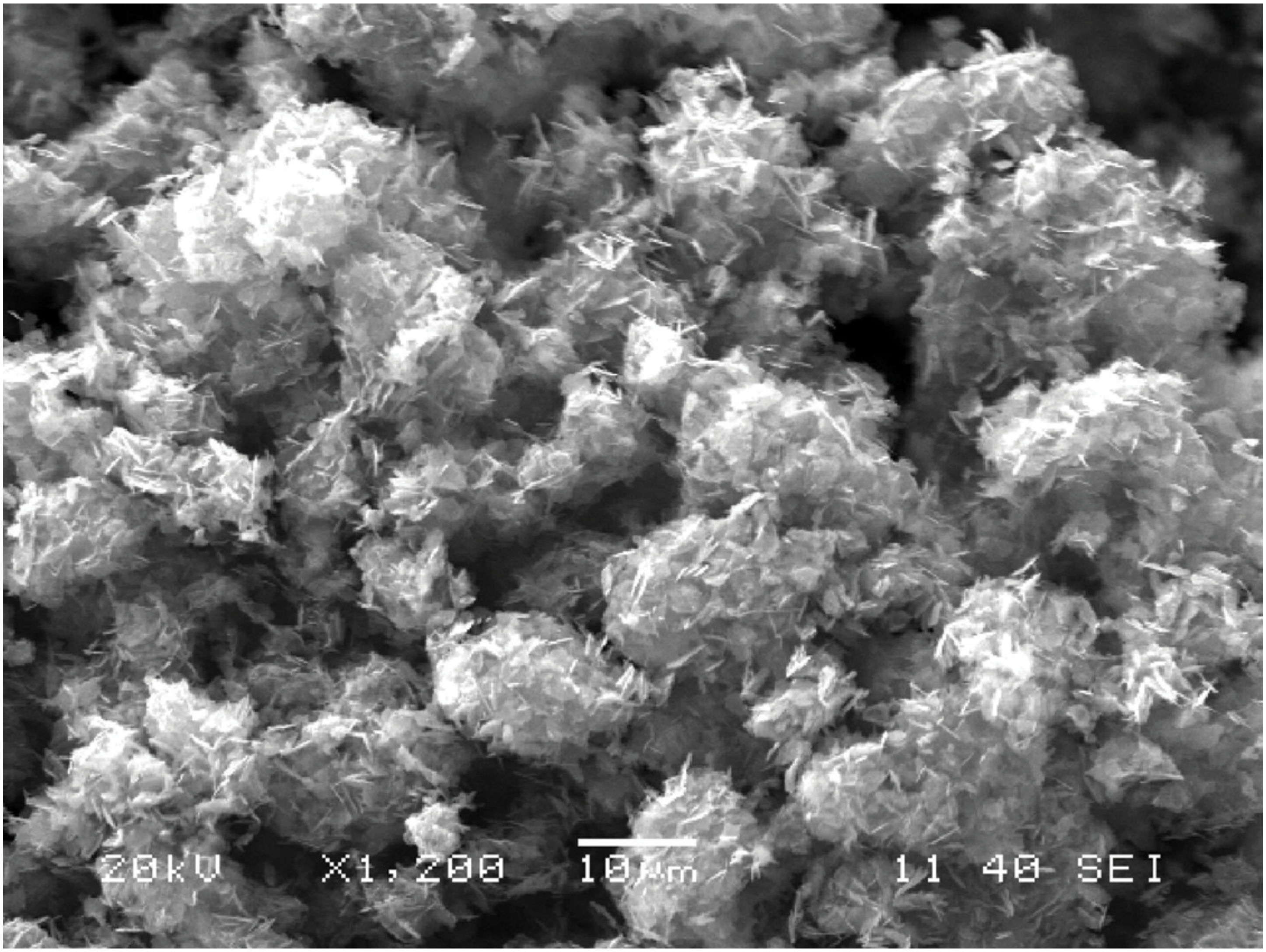
Lithium Use in Batteries



Circular 1371

U.S. Department of the Interior
U.S. Geological Survey

On the cover. Flakes of lithium manganese phosphate can serve as electrodes for batteries. Photograph by the Pacific Northwest National Laboratory (http://www.pnl.gov/news/release.aspx?id=814).

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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2012

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Contents

Figures

Tables

Conversion Factors and Datum

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)
metric ton (t)	1.102	ton, short (2,000 lb)
	Energy	
kilowatthour (W)	3,600,000	joule (J)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

As used in this report, one mass unit of lithium carbonate produces 0.1879 mass unit of lithium (thus, to produce one mass unit of lithium requires 5.3220 mas units of lithium carbonate).

Abbreviations and Acronyms

DOE	U.S. Department of Energy
EV	electric vehicle
HEV	hybrid electric vehicle
Li	lithium
Ni-MH	nickel-metal hydride
PHEV	plug-in hybrid electric vehcle
RBRC	Rechargeable Battery Recycling Corporation
INMETCO	International Metals Reclamation Company, Inc.
USGS	U.S. Geological Survey

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Abstract

Lithium has a number of uses but one of the most valuable is as a component of high energy-density rechargeable lithium-ion batteries. Because of concerns over carbon dioxide footprint and increasing hydrocarbon fuel cost (reduced supply), lithium may become even more important in large batteries for powering all-electric and hybrid vehicles. It would take 1.4 to 3.0 kilograms of lithium equivalent (7.5 to 16.0 kilograms of lithium carbonate) to support a 40-mile trip in an electric vehicle before requiring recharge. This could create a large demand for lithium. Estimates of future lithium demand vary, based on numerous variables. Some of those variables include the potential for recycling, widespread public acceptance of electric vehicles, or the possibility of incentives for converting to lithium-ion-powered engines. Increased electric usage could cause electricity prices to increase. Because of reduced demand, hydrocarbon fuel prices would likely decrease, making hydrocarbon fuel more desirable.

In 2009, 13 percent of worldwide lithium reserves, expressed in terms of contained lithium, were reported to be within hard rock mineral deposits, and 87 percent, within brine deposits. Most of the lithium recovered from brine came from Chile, with smaller amounts from China, Argentina, and the United States. Chile also has lithium mineral reserves, as does Australia. Another source of lithium is from recycled batteries. When lithium-ion batteries begin to power vehicles, it is expected that battery recycling rates will increase because vehicle battery recycling systems can be used to produce new lithium-ion batteries.

Introduction

Lithium is the lightest metal and the least dense solid element and, in the latter part of the 20th century, became important as an anode material in lithium batteries. The element's high electrochemical potential makes it a valuable component of high energy-density rechargeable lithium-ion batteries. Other battery metals include cobalt, manganese, nickel, and phosphorus. Batteries are ubiquitous in advanced economies, powering vehicle operations, sensors, computers, electronic and medical devices, and for electrical grid-system load-leveling and are produced and discarded by the billions each year. There is concern that the demand for battery metals could increase, possibly to the point at which a shortage of these metals will occur. Lithium is of particular interest because it is the least likely of the battery metals to be replaced by substitution because it has the highest charge-to-weight ratio, which is desired for batteries in transportation applications.

Lithium batteries already enjoy a sizeable market, powering laptop computers, cordless heavy-duty power tools, and hand-held electronic devices. But an even greater market could exist for lithium as a component of electric and hybrid vehicle batteries and for alternative energy production. Concerns about the carbon dioxide footprint of hydrocarbon-based powerplants and internal-combustion-powered automobiles, the projected hydrocarbon shortage (which could mean high prices) in coming years, and U.S. dependency on foreign hydrocarbon fuels have spurred great interest in alternative energy sources. Electric-powered vehicles are expected to take market share from internal-combustion-powered vehicles in the future. Large batteries are and will continue to be needed for powering all-electric and hybrid vehicles and also for load leveling within solar- and wind-powered electric generation systems. Research on lithium for use in large batteries is in advanced stages. Future light vehicles will potentially be powered by electric motors with large, lightweight batteries, and lithium is a particularly desirable metal for use in these batteries because of its high charge-to-weight ratio. Table 1 shows the plans of automobile manufacturing companies, as of 2010, for introducing lithium-ion-powered vehicles.

This report addresses some of the issues raised by the increased focus on lithium, including the context of the lithium market into which future lithium-based large batteries must fit, the projected effect of electric and hybrid cars on lithium demand, various estimates for future lithium demand, and obstacles to reaching the more optimistic estimates.

Table 1. Announced introductions of lithium-ion powered automobiles through July 2010.

[Data are from Ford Motor Company (2009), Kanellos (2009), Toyota Motor Sales, U.S.A., Inc. (2009), Abuelsamid (2010), American Honda Motor Co., Inc. (2010), China Car Times (2010), Ewing (2010), General Motors Company (2010), Green Car Reports (2010), Murray (2010), Nissan (2010), Osawa and Takahashi (2010), and Tesla Motors (2010). JV, joint venture; kW, kilowatt; kWh, kilowatthour; mph, miles per hour; V, volt]

Automobile manufacturer	Vehicle name (type)	Date of introduction	Comments
Audi	E-Tron (pure electric)	2013	Concept sports car. Lithium-ion battery powered motor on each wheel.
BYD (China)	E6 (pure electric)	2010	Currently being tested by Shenzhen Taxi Co. Iron-based lithium-ion battery. About $43,000 retail (before 20 percent government subsidy).
BMW	Mega City (pure electric)	2013	Planning stage.
Chrysler	Fiat 500EV (pure electric)	2012	Lithium-ion battery pack. Estimated range 80-100 miles. Expect to use U.S.-produced battery.
Ford	Ford Fusion BEV (pure electric)	2011	Currently testing concept cars. Lithium-ion battery pack. Capacity of 23 kWh and a range of up to 75 miles. Charging the batteries will take between 6 and 8 hours, using a household 230-V electricity supply.
General Motors	Chevrolet Volt (pure electric)	2011	Concept car exists. Powered by lithium-ion battery pack, which will be manufactured in the United States.
Honda	FCX Clarity (fuel cell)	2010	Hydrogen-powered fuel cell. Lithium-ion battery for supplemental power.
Hyundai	Blue-Will (plug-in hybrid)	2012	Lithium-ion battery powered.
Mercedes Benz	SLS AMG (pure electric)	2013	Concept sports car. Hydrogen fuel cell plus lithium-ion battery.
Nissan	LEAF (plug-in hybrid)	2012	May 26, 2010, broke ground for: Auto plant 150,000-vehicle-per-year capacity. Lithium-ion battery plant 200,000 unit-per-year capacity.
Tesla	Roadster (pure electric)	2008	Currently marketing electric automobiles. Lithium-ion battery pack (liquid cooled); 900 pounds, storing 56 kWh of electric energy, delivering 215 kW of electric power
Toshiba-Mitsubishi JV	Unspecified	unspecified	Hopes to sell lithium-ion batteries for future Mitsubishi Motors vehicles.
Toyota	Prius-PHV (plug-in hybrid)	2010	Test program, 500 vehicles placed worldwide. First generation lithium-ion battery. Maximum range (fully electric) = 13 miles. Maximum speed (fully electric) = 60 mph.
Volkswagen	e-Golf (pure electric)	2013	To be tested in 2011. Air-cooled 26.5 kW lithium-ion battery pack. Expect 93 miles on one charge.

Lithium Demand

Lithium Consumption Statistics

Apparent consumption of lithium in the United States has been recorded since at least 1900 (fig. 1) and includes only imports minus exports because lithium is not mined domestically. Significant apparent consumption began in the 1950s, peaked in 1974, and has shown a slightly decreasing trend since 1974. The consumption figures do not include lithium contained in imported finished assemblies, for example, lithium contained in batteries (almost all of which are manufactured overseas) that are within computers, electronic devices, and tools.

In 2007 and 2008, an estimated 25,400 metric tons (t) of lithium was used each year for various products worldwide. Owing to the general downturn in the world economies, total lithium use in 2009 decreased to approximately 18,000 t. Table 2 lists the percentage of lithium used worldwide in each product during those 3 years, as estimated by the U.S. Geological Survey (Jaskula, 2008–2010). Of particular significance, the lithium use in batteries decreased by approximately 2,062 t, or 35 percent, between 2008 and 2009. Lithium use in rechargeable batteries increased from zero in 1991 to 80 percent of the market share in 2007, with 1992 being the first time nickel-cadmium and nickel-metal-hydride (NiMH) batteries started to be replaced by lithium-ion batteries (fig. 2). The greater charge-to-density (power-to-weight) ratio of lithium is favorable for electronic devices and has helped to drive this trend.

Table 2. World market shares for various lithium end-uses from 2007 through 2009.

[World market share is expressed as a percentage (%) of the total global sales of lithium; production is in metric tons of contained lithium. Data are from Jaskula (2008–2010)]

End-use	2007	2008	2009
World market share:			
Ceramics and glass	18%	31%	30%
Batteries	25%	23%	21%
Lubricating greases	12%	10%	10%
Pharmaceuticals and polymers	7%	7%	7%
Air conditioning	6%	5%	5%
Primary aluminum (alloying)	4%	3%	3%
Other	28%	21%	24%
World production, in metric tons of contained lithium	25,400	25,400	18,000

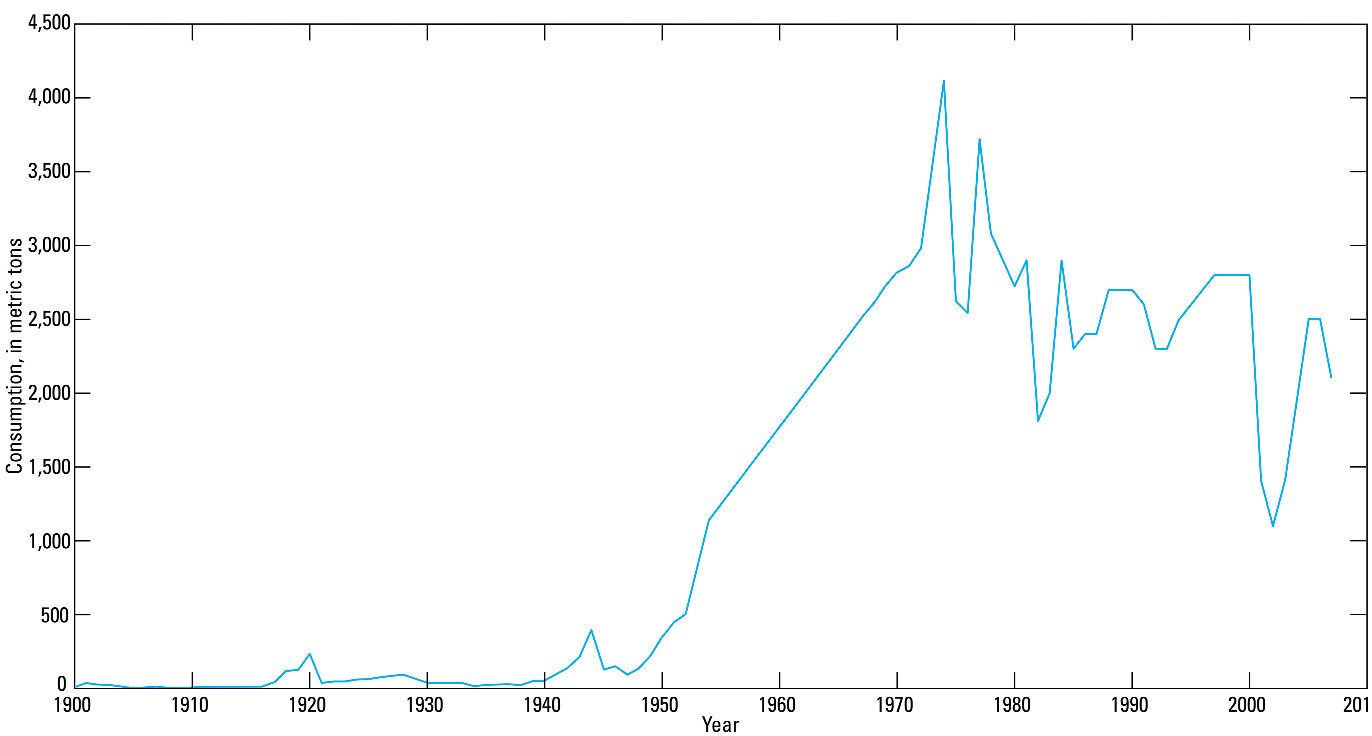

Figure 1. Chart showing consumption of lithium in the United States from 1900 through 2007. Values are in metric tons. Data are from U.S. Geological Survey (2010).

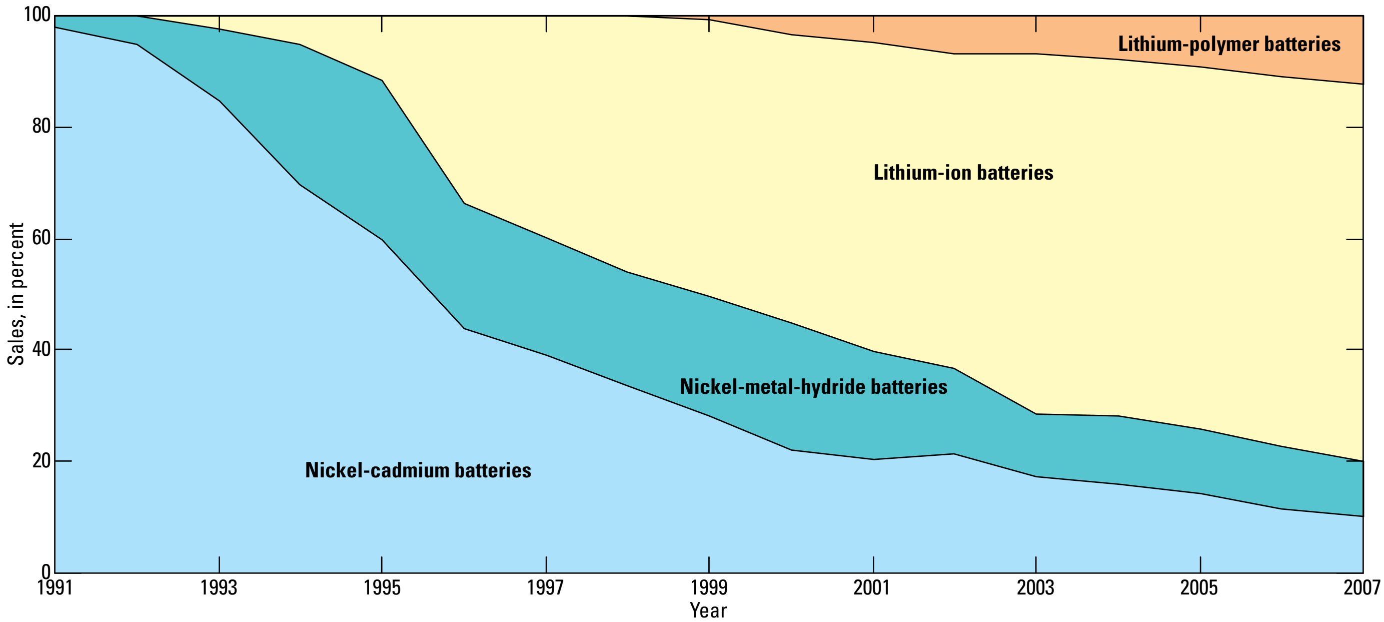

Figure 2. Chart showing sales of rechargeable batteries worldwide from 1991 through 2007. Values are expressed as percentage of total global sales of rechargeable batteries. Data are from Wilburn (2007) and Takashita (2008).

Effect of Electric and Hybrid Cars on Lithium Demand

Although electric vahicles have existed for more than a century, Toyota's hybrid Prius was the first to have commercial success. Now many automobile manufacturers are expanding into cutting-edge electromotive powertrains (table 1; Hsiao and Richter, 2008). Electric cars are characterized as—all electric (EV), hybrid (HEV), or plug-in hybrid (PHEV) vehicles. Concerns about the dependence on imports of oil and about the carbon footprint of internal-combustion engines in current automobile industry products have created this interest in electric vehicles. In fact, the U.S. Government planned to provide $11 billion in loans and grants to car and battery makers to reduce the country's dependence on foreign oil (Smith and Craze, 2009). These funds will be targeted for research and development and for production and recycling facilities.

Through 2010, the predominant battery technology powering experimental electric vehicles has been NiMH, although the General Motors EV–1 was powered by a lead-acid battery. NiMH batteries offer proven performance, reasonable energy density, and thermal stability. They are also large, heavy, and expensive and require a long time to charge compared with lithium-ion batteries. In 2008, attention was directed toward lithium-ion batteries as an alternative, although safety, longevity, and cost were of concern (Hsiao and Richter, 2008). The high charge-to-weight ratio of lithium makes the lithium-ion battery much lighter than the NiMH battery, which is desirable for powering electric vehicles. Although NiMH batteries are affected by the "memory effect" (the battery loses its capacity when it is recharged without being fully depleted), lithium-ion batteries are not (PlanetWatch, 2009). These qualities have helped to bring lithium-ion technology to the forefront as the object of extensive research (Gaines and Cuenca, 2000). In automotive applications, individual cells are typically connected together in various configurations and packaged with associated control and safety circuitry to form a battery module (Anderson, 2009). Therefore, though most research is directed toward improving lithium-ion battery technology at the cell level, research is likely to also be directed toward determining the most effective cell configurations and packaging.

Depending on lithium-ion battery chemistry, it would take 1.4 to 3.0 kilograms (kg) of lithium equivalent (7.5–16.0 kg of lithium carbonate) to support a 40-mile trip in an electric vehicle before requiring recharge (Gaines and Nelson, 2009). If the trend toward replacing internal combustion engine vehicles with electric vehicles continues and lithium-ion batteries become the preferred power source for electric vehicles, then a large demand for lithium carbonate could potentially be generated.

Estimates of Future Lithium Demand

Several authors have estimated future lithium demand using certain assumptions and projections of electric car demand. Gaines and Nelson (2009) optimistically calculate that U.S. annual demand for electric vehicles might require as much as 22,000 t of lithium (117,000 t of lithium carbonate) by 2030, and as much as 54,000 t (287,000 t of lithium carbonate) by 2050, assuming the lithium-nickel-cobalt-graphite chemistry that is currently popular. This projection further assumes continued growth in all automobile sales, 52 percent electric vehicle penetration in 2030, and 90 percent in 2050, which Gaines and Nelson admit are optimistic assumptions.

Tahil (2007, 2008) expressed concern that, if the 60 million cars that are produced worldwide each year were totally replaced with plug-in hybrids, each having a 5-kilowatt battery (requiring about 1.40 kg of lithium carbonate), demand for lithium carbonate would be 420,000 t annually, which is nearly 5 times the current lithium carbonate production. This would place an unsustainable demand on lithium resources because of geochemical constraints in extracting the product from known deposits. In July 2009, Chemetall GMBH, a division of Rockwood Holdings, Inc., which holds 30 percent of the global lithium carbonate market share, estimated that lithium carbonate demand in 2020 would be either 145,000 t (42 percent automotive) or 116,000 t (27 percent automotive), depending on if Gaines and Nelson's (2009) or Tahil's (2007, 2008) scenario was used (Haber, 2008; Chemetall, 2009).

These new lithium demand estimates, which are derived from expected use of lithium in next-generation electric vehicles, vary. One must understand the assumptions, including the potential for recycling, that underlie published estimates. Before any of the more optimistic estimates for lithium demand are actualized, some significant obstacles must be overcome. These are summarized below.

The lithium-based battery packs used in automobiles are much larger than the small lithium-ion batteries currently being produced for use in electronic devices. While technical testing has been encouraging, large-scale lithium-ion battery packs have not been fully market tested (table 1). The level of use that electric vehicles achieve will depend in part on consumer acceptance. Product safety, convenience of use, reliability, and cost of purchase and operation are likely to influence consumer acceptance.

Electric-powered vehicles currently cost more than equivalently-sized vehicles powered by internal combustion. For electric vehicles ti become cost effective, the savings from using electric power would have to offset the incremental capital cost (Simpson, 2006) and the cost of operating the vehicle.

Competition between the price of electricity and the price of grasoline will affect the adoption of electric vehicles. The price of gasoline is set by market forces and changes as levels of consumption change. The price for electric power is usually set by regulatory bodies and is therefore less responsive to changes in use.

The adoption of electric vehicles is likely to be constrained by the capacity of the electricity grid unless electric vehicles are recharged during off-peak times. Changes in the pricing of recidential electricity and the use of devices such as smart meters would have an affect (Xcel Energy Inc., 2010).

Lithium Supply

The two most important sources of lithium are a hard silicate mineral called spodumene, which is found in pegmatites, and brine lake deposits that contain lithium chloride. In 2009, of the worldwide reported lithium reserves, expressed in terms of contained lithium, 13 percent was reported to be within hard rock mineral deposits, and 87 percent, within brine deposits (Jaskula, 2009, 2010). Reserves are known quantities that are presently economic to exploit (U.S. Bureau of Mines and U.S. Geological Survey, 1980).

Production of lithium carbonate from spodumene is more energy intensive compared with production from brine and is more costly because of added extraction and beneficiation challenges. Comparing lithium production from these two sources between 1990 and 2008 (fig. 3), the compound annual growth rate (CAGR) of lithium from brine deposits has been 11.7 percent per year, whereas lithium's CAGR from hard rock deposits has been 7.4 percent per year. Overall, the CAGR of lithium production from 1990 to 2008 was 10.4 percent.

In 2008, Australia produced most of the lithium from hard rock (table 3). Most of the lithium recovered from brine came from Chile, with smaller amounts from China, Argentina, and the United States. Chile has two producers of lithium products, Sociedad Química y Minera de Chile S.A. (SQM) and Chemetall SCL. Both companies operate at the Salar de Atacama, Chile, and account for more than 65 percent of the world lithium market (Lithium Site, 2009). The Salar de Atacama holds about 29 percent of the world's known lithium resources, and together, the salt lakes of South America (Argentina, Bolivia, and Chile) contain about 75 percent of the world's known lithium resources (Jaskula, 2010, p. 93). At SQM's operation, the brine is pumped from about 40 meters (m) below the surface and then placed in surface ponds, where it is exposed to evaporation under conditions of high heat, low humidity, and strong surface winds (Energy Investment Strategies, 2008). The resulting lithium chloride concentrate is further treated with sodium carbonate to produce the desired lithium carbonate. In 2008, SQM's annual capacity of lithium carbonate production at the Salar de Atacama was expanded to 40,000 metric tons per year (t/yr); meanwhile, Chemetall maintained capacity of 27,000 t/yr at the Salar de Atacama (Chemetall, 2009; de Solminihac, 2009).

Argentina has at least two brine deposits of importance. The Salar del Hombre Muerto operation, which is at 3,962 m above sea level and operated by FMC Corporation, is recovering lithium using a proprietary separation process (Lithium Site, 2009). Production capacity at the Salar del Hombre Muerto, is 12,000 t/yr of lithium carbonate and 6,000 t/yr of lithium chloride (Tahil, 2007). In January 2007, the brine operation Salar del Rincon opened pilot-plant-scale

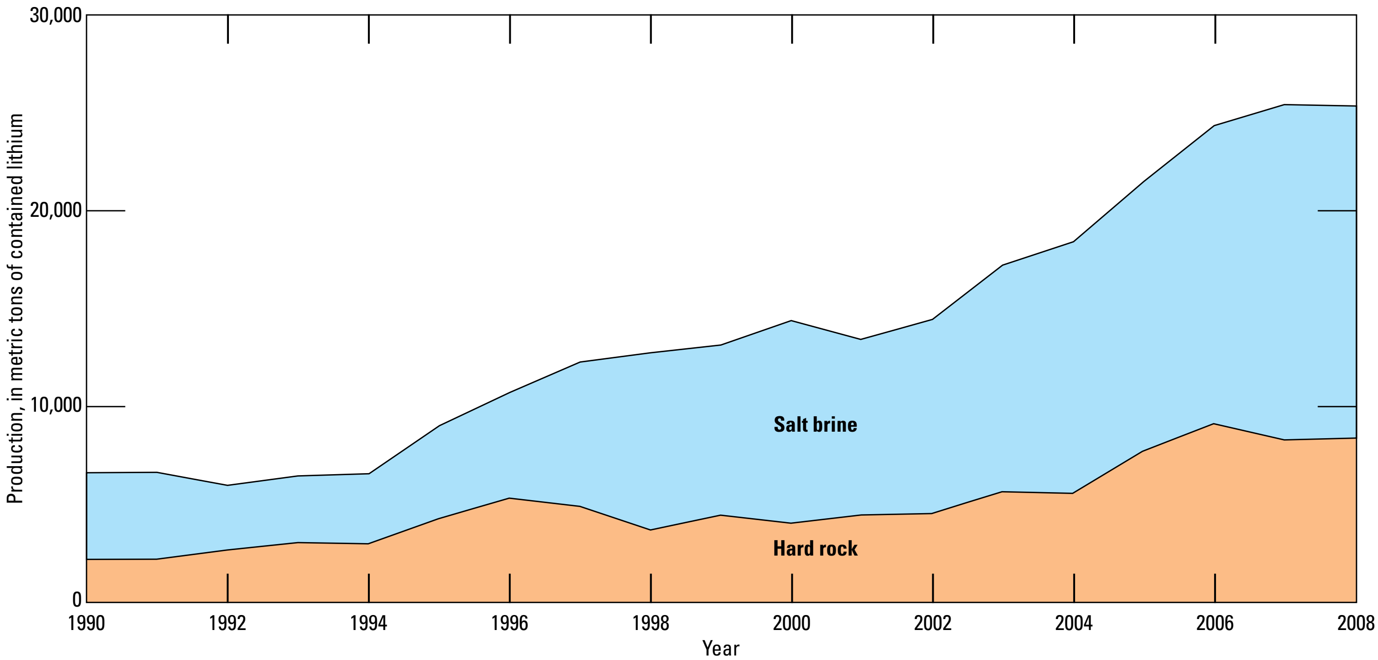

Figure 3. Chart showing production of lithium, by deposit type, worldwide from 1990 through 2008. Values are in metric tons of contained lithium. Data are from U.S. Bureau of Mines (1992–1995) and U.S. Geological Survey (1996–2009).

Table 3. World production of lithium from minerals and brine in 2008, by country.

[Values are in metric tons of contained lithium. Production data are estimated and rounded to no more than three significant digits. Table includes data available through April 1, 2009. Data are from Jaskula (2008) and Tahil (2008). LiCl, lithium chloride; Li_2CO_3, lithium carbonate; NA, not available]

Country[1]	Deposit type	Lithium product	Production
Production from minerals:			
Australia	Spodumene	Concentrate	6,280
Brazil	Various	Concentrate	160
Canada[2]	Spodumene	Concentrate	690
China	Various	Li_2CO_3	880
Portugal	Lepidolite	Concentrate	700
Zimbabwe	Various	Concentrate	500
Total			9,210
Production from brine:			
Argentina[3]	NA	Li_2CO_3	1,880
	NA	LiCl	1,290
Chile[3]	NA	Li_2CO_3	9,870
	NA	LiCl	720
China	NA	Li_2CO_3	2,410
United States[4]	NA	Li_2CO_3	1,710
Total			17,900

[1]Other countries produce small amounts of lithium but are not included here.

[2]Based on all Canada's spodumene concentrates (Tantalum Mining Corp. of Canada Ltd., Tanco property).

[3]New information was available from Argentine and Chilean sources, prompting major revisions in how lithium production was reported.

[4]The estimate for the United States is taken as the suggested production of Chemetall's Clayton Valley mine at Silver Peak, Nevada, as reported by Tahil (2008, p. 20).

operations in Argentina (Tahil, 2007); the operations were still under development in 2010.

China is also a major lithium producer (13 percent of world production of contained lithium). Salt lakes are widely distributed across China's western Qinghai, Tibet, Xinjaing and inner Mongolia, with rich resources of boron, lithium, magnesium, and potassium (Ma, 2000). China is currently developing three brine lake deposits—the Taijinaier salt lake in Qaidam Basin, Qinghai Province, north of Tibet; the Dangxiongcuo (DXC) salt lake in southwestern Tibet; and the Zhabuye salt lake in western Tibet (Tahil, 2007, p. 10). With the success of a 500-t/yr pilot plant at Taijinaier salt lake, CITIC Guoan Scientific and Technical Company inaugurated a 35,000-t/yr lithium carbonate plant in 2007 (Zhang, 2009). The Canadian company Sterling Group Ventures is considering development of a 5,000-t/yr lithium carbonate plant at DXC salt lake (Zhang, 2009). The Zhabuye salt lake—the third largest salt lake (in terms of area) in the world—is at 4,400 m above sea level and is the largest lithium deposit in China (Green Energy News, 2008). In 2008, Baiyin Zhabuye Lithium Industries Co., Ltd, produced 2,000 t of lithium carbonate and lithium hydroxide from this deposit and has government approval to increase lithium carbonate production capacity by 12,000 t/yr (Zhang, 2009).

The brines of the Salar de Uyuni in Bolivia are also a potential source of lithium carbonate. The deposit contains approximately 9 million metric tons of lithium and could account for as much as 50 percent of the global lithium reserves; it is currently under consideration for development (Tahil, 2007). The government of Bolivia has sought to keep its development under government auspices and has begun to build a 30,000-t/yr lithium carbonate production facility at the deposit (New Tang Dynasty Television, 2009).

These brine lake deposits and other deposits not specifically discussed in this report each have unique characteristics with respect to lithium content, salt chemistry, and general ease (cost) of processing. The market together with the governments' willingness to subsidize lithium supply and demand, either directly or indirectly through tax-modified behavior, will determine where the lithium is produced and the reserve estimates of the moment.

Brine-originated lithium carbonate, the primary ingredient in lithium-ion batteries, accounted for about 67 percent of lithium production (excluding the United States) in 2008. Lithium carbonate can be made from lithium concentrate, but it is more expensive to do so (Tahil, 2007). Supply and demand for lithium is currently balanced. Expansion of worldwide brine operations is dependent upon lithium carbonate from brines beings less expensive than from competing sources and an expanding lithium-based battery market to serve an assumed growing electric vehicle market.

Lithium Carbonate Prices

The prices of lithium carbonate (Li_2CO_3) imported into the United States from 1989 through 2008 are shown in figure 4. The unit value of U.S. imports was used because it is presumably more representative of world prices than the unit value of U.S. exports, which are more refined and a higher priced form of lithium carbonate.

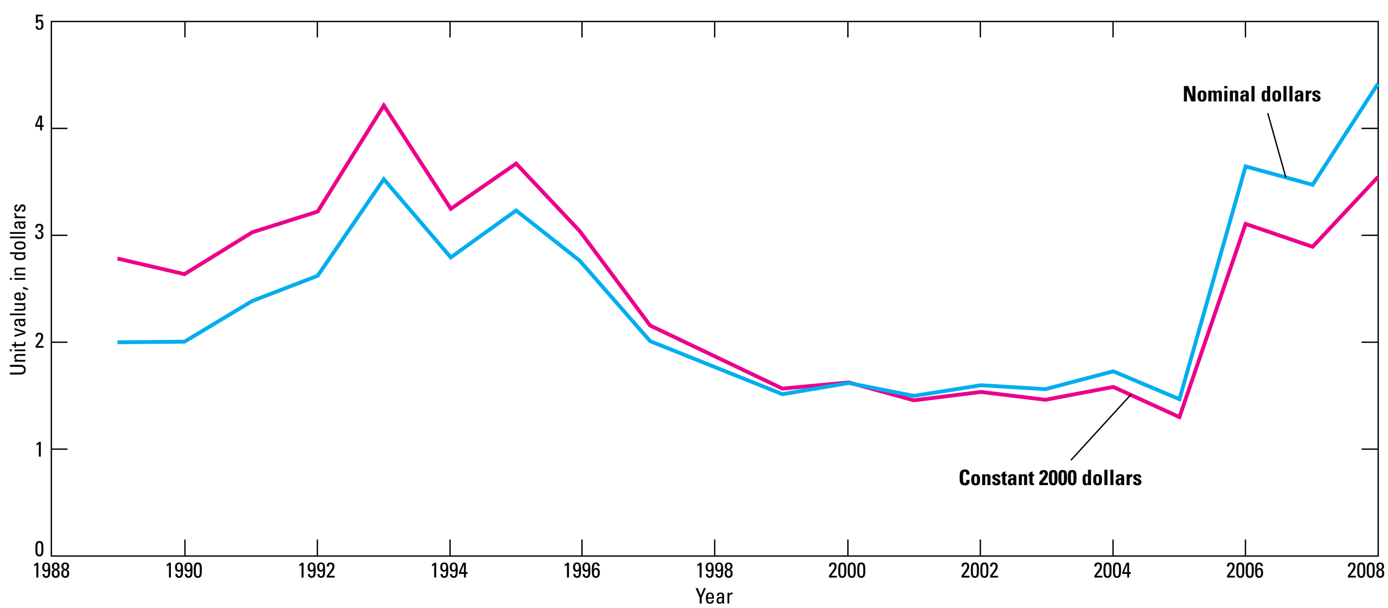

Figure 4. Chart showing the unit value of imports of lithium carbonate into the United States from 1989 through 2008. Values are in dollars per kilogram of lithium carbonate. Data are from U.S. Geological Survey (1996–2009) and U.S. Bureau of Mines (1992–1995).

The unit value of imports of lithium carbonate into the United States decreased from 1995 through 1999, reflecting growth in supply of lithium carbonate from low-cost brine deposits (fig. 3). The period from 1999 through 2005 experienced nondynamic supply and demand activity. From 2006 through 2008, increased demand for lithium carbonate resulted in higher prices, leading to increased investment in exploration and new capacity development.

Because automobile batteries are expected to become (although they are not yet) a major factor in total battery demand, there is some concern about whether world lithium reserves will be sufficient to supply a future surge in automobile-generated lithium demand (Tahil, 2007, 2008). Others are less concerned (Pease, 2008; Beckdorf and Tilton, 2009; Gaines, 2009; Gaines and Nelson, 2009). Historically, reported reserve levels were not limits but rather were indicative of actual market conditions at the time of assessment.

Lithium Batteries

Battery Types

Lithium batteries contain metallic lithium and are not rechargeable. The button-sized cells that power watches, hand-held calculators, and small medical devices are usually lithium batteries. These are also called primary lithium batteries, and they provide more useable power per unit weight than do lithium-ion batteries (called secondary batteries). Lithium-ion batteries use lithium compounds, which are much more stable (less likely to oxidize spontaneously) than the elemental lithium used in lithium batteries (Green Batteries, 2009).

There are many lithium-ion battery types and configurations. These batteries are not generally available in standard household sizes but rather are manufactured specifically for a particular electronic device. It is possible to classify lithium-ion battery types according to battery chemistry and packaging. Table 4 lists the most common rechargeable lithium-ion chemistries.

One or more of the lithium-ion battery chemistries displayed in table 4 or another entirely different lithium-ion battery chemistry may become the basis for the future electric vehicle power supply. The major difference between batteries for electronics and batteries for electric vehicles will be size. Increased size can be obtained by making assemblies of small cells or by developing singular large cells. A detailed cost and technical study of lithium-ion battery development for automobiles is beyond the scope of this report but can be found in Gaines and Cuenca (2000), Hsiao and Richter (2008), Anderson and Patiño-Echeverri (2009), Burke and Miller (2009), Nelson, Santini, and Barnes (2009), and National Institute of Advanced Industrial Science and Technology [Japan] (2009).

Rechargeable lithium-ion batteries can be categorized by packaging in the following categories:

- cylindrical cells, which are the most widely used packaging for wireless communication, mobile computing, biomedical instruments, and power tools (Buchmann, 2004)
- prismatic cells, which were developed in the early 1990s, are made in various sizes and capacities, and are custom made for electronic devices, such as cell phones (Buchmann, 2004)
- pouch cells, which were introduced in 1995, permit tailoring to the exact dimensions of the electronic device manufacturer, and are also easily assembled into battery packs as needed (Buchmann, 2004)

Table 4. Common lithium-ion rechargeable battery chemistries.

[Associated data are in specified units. Data are from Buchmann (2006), Burke and Miller (2009), and Gaines and Nelson (2009). Ah/g, ampere-hours per gram; Al, aluminum; Co, cobalt; Fe, iron; Li, lithium; Ni, nickel; Mn, manganese; O, oxygen; PO_4, phosphate; Wh/kg, watthours per kilogram]

Cathode name and chemistry	Cell voltage		Electric charge, Ah/g		Energy density, Wh/kg	Applications
	Maximum	Nominal	Anode	Cathode		
Cobalt, Li(Ni 0.85, Co 0.1, Al 0.05)O_2	4.2	3.6	0.36	0.18	100–150	Cell phone, cameras, laptops.
Manganese (spinel), ($LiMn_2$)O_4	4.0	3.6	0.36	0.11	100–120	Power tools, medical equipment.
Nickel, cobalt, manganese, Li(Ni 0.37, Co 0.37, Mn 0.36)O_2	4.2	3.6	0.36	0.18	100–170	Power tools, medical equipment.
Phosphate, (Li,Fe)PO_4	3.65	3.25	0.36	0.16	90–115	Power tools, medical equipment.

Battery Production

Through 2009, lithium-ion (rechargeable) battery production in the United States has been limited to small-scale, high-profit-margin niche markets, such as medical, military, or space applications, and the greater part of general-use lithium-ion batteries has been produced in China, Japan, and the Republic of Korea (Wilburn, 2008, p. 3). In 2009, General Motors announced the construction of a lithium-ion battery pack production plant to be located in Warren, Michigan, which will produce vehicle batteries for the its new electric car, the Volt, which is scheduled to premier in 2011 (Brooke, 2009).

Japan is a major producer of lithium-based batteries. In 2009, lithium-based batteries accounted for 43 percent of the total volume (4.34 billion units) of batteries produced in Japan—47 percent of lithium batteries were primary lithium batteries, and 53 percent were lithium-ion batteries (Battery Association of Japan, 2010).

Since lithium batteries first entered the market in 1993, about 45,000 t of lithium has been incorporated into these batteries worldwide. Figure 5 shows the annual and cumulative lithium battery production from 1993 through 2008.

Between 1993 and 2008, the lithium battery market consisted of nonrechargeable (primary) and rechargeable (secondary) batteries for electronic devices. Only about 0.2 percent of lithium produced went to automobile batteries in 2008 (Wilburn, 2008, p. 13).

Battery Recycling

In 2009, an estimated 3,700 t of lithium, contained in scrap batteries, became available to the world market. This estimate was determined by applying a Gaussian distribution to the annual production of batteries (expressed as contained lithium) for 2000–2008 and factoring in the average life of a lithium battery [assumed to be 4 years based on Dan's Data (2008), and Mah (2007)]. The actual amount of lithium recovered (worldwide) from recycled batteries in 2009 is not available for comparison to the amount available for recovery.

In the United States, it is unlikely that more than 20 percent of the batteries available for recycling actually were recycled. Europe, however, has stronger battery collection laws. Most scrap batteries in the United States have likely been sequestered either in homes and businesses or released to municipal solid waste to be retired to landfills or combusted. In 2006, lithium-ion batteries were not considered to be a hazardous waste in the United States (Mitchell, 2006).

When lithium-ion batteries begin to power vehicles, it is expected that battery recycling rates will increase because vehicle battery recycling systems, based on the lead-acid model currently in place, can be used to produce new

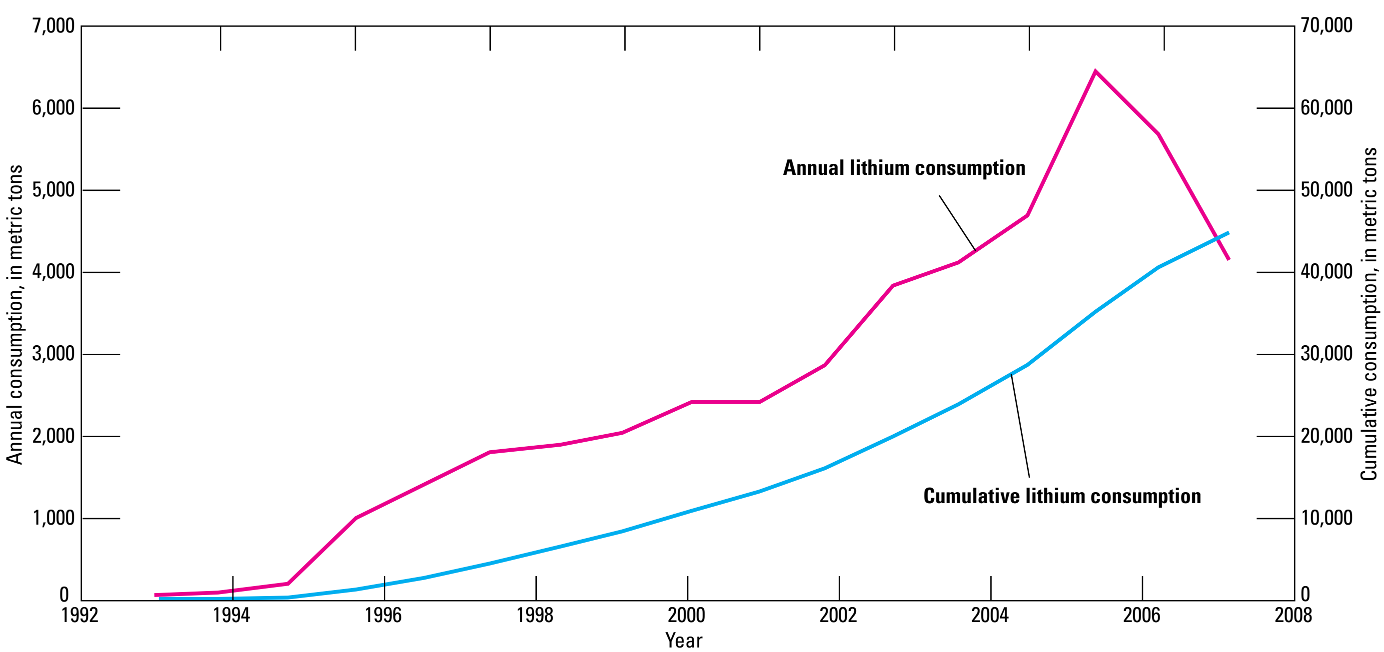

Figure 5. Chart showing lithium consumed in battery production worldwide from 1993 through 2009. The red line shows the amount of lithium used worldwide for each year, and the blue line shows the total amount of lithium used worldwide in production of batteries. Values are in metric tons of contained lithium. Data are from U.S. Geological Survey (1996–2010), Jaskula (2008–2010), and Takeshita (2008).

lithium-ion batteries. Recycling of electric vehicle batteries could provide 50 percent of the lithium requirement for new batteries by 2040 (Chemetall, 2009; Gaines, 2009).

Most if not all types of batteries can be recycled. It costs about $1,100 to $2,200 to recycle 1 t of batteries of any chemistry and size (including small cells), except automobile batteries. Significant subsidies are still required from manufacturers, agencies, and governments to support the battery recycling programs (Buchmann, 2009).

A high-energy (100 ampere-hour) battery processed through recycling would return about 169 kg of lithium carbonate, 38 kg of cobalt, and 201 kg of nickel [calculated from data reported by Hsiao (2008, p. 22)]. This estimate is based on the assumptions that the cost of recycling large automobile batteries is similar to that for small batteries; the automobile battery cathode chemistry will be $Li[Ni\ 0.8, Co\ 0.15, Al\ 0.05]O_2$, and 98 percent of the metal will be recovered in recycling. At 2008 prices (normalized to 2000 dollar basis) for lithium carbonate and cobalt-nickel metals, the value of the recovered materials would be about $6,400. At 2009 prices, which were very similar to 2005 prices for these materials, the value of the recovered materialswould be about $4,100. Metal pricing will be very important to recycling profitability. Lithium carbonate return contributes only about 10 percent of the total monetary return. If research takes cathode technology to less expensive metals, such as manganese and phosphorus, then the economic attractiveness of recycling these batteries could diminish, perhaps to a point at which recycled lithium carbonate cannot be counted on to supplant pressure on in-ground lithium resources.

The same methodology and assumptions applied to the high-power (10 ampere-hour) battery cut all of the monetary returns by roughly one-half, placing the recycling decision very close to the break-even level. The economics of lithium ion battery recycling needs more research. Xu and others (2008) reviewed the research conducted on this subject through 2007.

The Rechargeable Battery Recycling Corporation (RBRC) was founded in 1994 to promote recycling of rechargeable batteries in North America (table 5). RBRC is a nonprofit organization that collects batteries from consumers and businesses and sends them to North American recycling organizations, such as International Metals Reclamation Company, Inc. (INMETCO) and Toxco Inc. Since 1992, Sony has partnered with Sumitomo Metals to recover cobalt from used lithiumi-ion batteries (Hsiao, 2008).

For most lithium-ion batteries, lithium represents less than 3 percent of the production cost; nickel and cobalt are the biggest economic drivers of recycling (Hamilton, 2009). Toxco is North America's leading battery recycler and has been recycling single-charge and rechargeable batteries used in electronic devices and industrial applications since 1992 at its Canadian facility in Trail, British Columbia (Hamilton, 2009). Toxco can recover up to 98 percent of the lithium carbonate from lithium waste but focuses on cobalt and nickel (Hsiao, 2008).

Table 5. European and North American lithium battery recyclers.

[Battery processing capacity values are in metric tons per year. Data are from Tollinsky (2008), Toxco Inc. (2009), and European Battery Recycling Association (2009)]

Region/country	Company	City, State/Province/region	Capacity
		Europe	
Switzerland	Batrec Industrie AG	Wimmis, Bern	5,000
France	Citron	Rogerville, Seine-Maritime	130,000
	Eurodieuze Industrie	Dieuze, Moselle	NA
	Recupyl	Domène, Isère[1]	110
	S.N.A.M.	Viviez, Aveyron	4,000
Belgium	Umicore	Olen, Antwerp	3,000
		North America	
Canada	Toxco, Inc.	Trail, British Columbia	NA
Canada	Xstrata Nickel International	Falconbridge, Ontario	3,000
United States	Toxco	Lancaster, Ohio	NA

[1]Pilot plant.

Lithium Battery Outlook

There exists already a large (billions of units per year) market for lithium and lithium-ion batteries, which are used to power hand-held electronic devices and for military purposes. These can be and are recycled using established practices. However, the recycling rate is unknown. Those batteries that are not recycled either go to landfills or remain uncollected at the user level.

If and when the electric motor replaces the internal combustion engine in cars and trucks, the demand for lithium as a major component of batteries, which is the focus of battery research, should increase accordingly. Lithium recycling for the increment of demand represented by automobile batteries that contain lithium should be practical and economical. The recycling would not only recover lithium but would also recover the more expensive metals, including cobalt and nickel. Lithium battery recyclers are already investing in capacity to do just that (Toxco Inc., 2009).

Available data are insufficient to project future lithium demand with certainty. Existing projections are speculative and largely assume a regular progression of automobile sales and an increasing share for electric vehicles. If the general economy remains constrained, then demand for lithium will likely be constrained accordingly. For the electric car share of the automobile market to grow, the relative cost of electric cars will have to decrease so that they are competitively priced compared with internal combustion-powered cars. Also, the cost of electric car batteries would have to drop with economies of scale. This, in turn, would be accompanied by a scale-up of the current (2010) lithium-ion battery technology to batteries of appropriate size for automobiles. To date, this scale-up is indicated, with a heavy research and development focus by battery producers.

Figure 6 shows the sales of hybrid automobiles and crude oil prices from 2000 through 2009. One should not infer a correlation of electric vehicle sales and oil prices from the figure. It is more likely that both are codependent on general economic activity levels. If lithium-containing batteries replace hydrocarbons for powering automobiles, then there will be upward pressure on the prices of the active metals that make up the cathodes of these batteries and possible downward pressure on hydrocarbon prices.

Existing lithium carbonate suppliers believe that they can accommodate the growing demand occasioned by a growing electric car market into the future (Chemetall, 2009; de Solminihac, 2009). The countries with extensive, relatively low-cost, lithium brine deposits are Argentina, Bolivia, Chile, China, and the United States. The marginal cost of lithium carbonate is mostly fixed by the cost of producing lithium carbonate from hard-rock spodumene deposits in Australia.

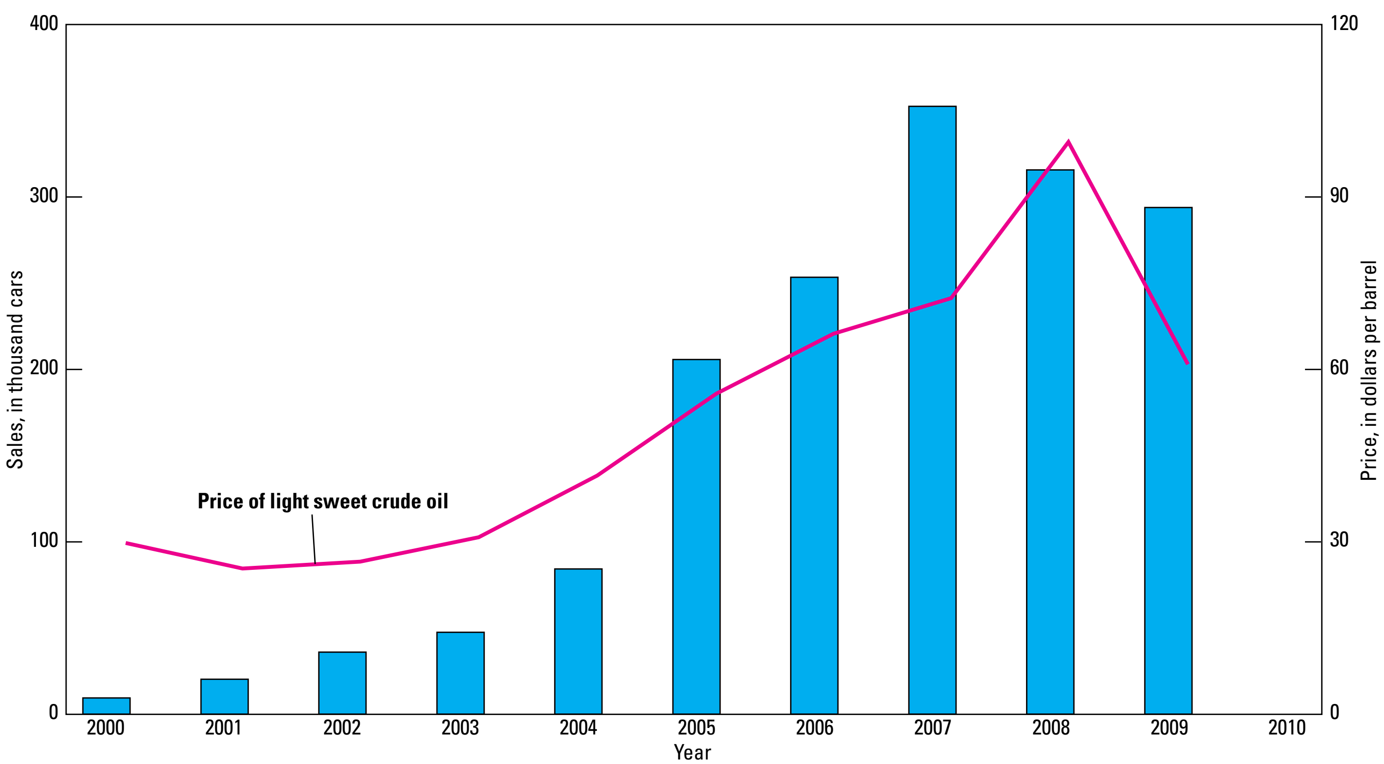

Figure 6. Graph showing sales of hybrid automobiles in the United States and the price of light sweet crude oil from 2000 through 2009. Figures are in numbers of automobiles sold and dollars per barrel. Data are from Hsiao (2008), Hybrid Cars (2010), Truck Trend (2009), and U.S. Department of Energy (2010).

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