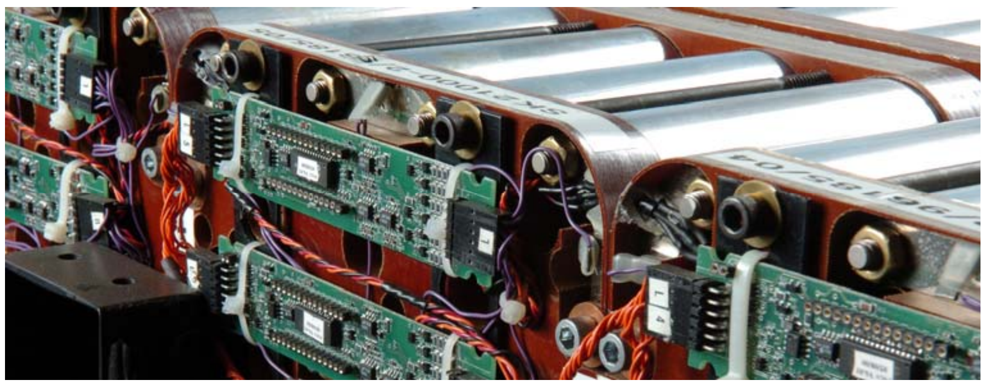
Lithium-ion Batteries for Electric Vehicles:

THE U.S. VALUE CHAIN



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Marcy Lowe, Saori Tokuoka, Tali Trigg and Gary Gereffi

Center on Globalization Governance & Competitiveness

Contributing CGGC researcher: Ansam Abayechi

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None of the opinions or comments expressed in this study are endorsed by the companies mentioned or individuals interviewed. Errors of fact or interpretation remain exclusively with the authors. We welcome comments and suggestions.

The lead author can be contacted at marcy.lowe@duke.edu.

List of Abbreviations

ANL	Argonne National Laboratory
ARRA	American Recovery and Reinvestment Act
BEV	Battery Electric Vehicle
CGGC	Center on Globalization, Governance & Competitiveness
CNT	Carbon nano-tubes
DOE	Department of Energy
EPA	Environmental Protection Agency
EV	Electric Vehicle
JV	Joint Venture
LBNL	Lawrence Berkeley National Laboratory
METI	Ministry of Economy, Trade And Industry in Japan
NaS	Sodium-Sulfur (battery)
NEDO	New Energy and Industrial Technology Development Organization (Japan)
Ni-Cd	Nickel Cadmium
Ni-MH	Nickel Metal Hydride
NREL	National Renewable Energy Laboratory
ORNL	Oakridge National Laboratory
PHEV	Plug-in Hybrid Electric Vehicle
R&D	Research and Development
SNL	Sandia National Laboratory
UPS	Uninterruptible Power Supply
V2G	Vehicle to Grid

Cover photo courtesy of Argonne National Laboratory

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Executive summary

The global motor vehicle industry is rapidly steering away from the internal combustion engine. Electric vehicles are increasingly attractive for their potential to reduce greenhouse gases and decrease dependence on oil. Market predictions vary widely, but most projections agree that a rapidly increasing share of new vehicle sales will consist of hybrid-electric, plug-in hybrid, and all-electric models. For automakers, the key to this dramatic shift will be lithium-ion batteries. While 96% of all hybrids available on the world market today run on nickel metal hydride batteries, within 10 years, 70% of hybrids, and 100% of plug-in hybrid and all-electric vehicles, are expected to run on lithium-ion (Deutsche Bank, 2009). If the United States is to compete in the future auto industry, it will need to be a major player in lithium-ion batteries.

Today's lithium-ion batteries, found in nearly all consumer electronics and made almost exclusively in Asia, will require additional technological advances before they can be applied widely to tomorrow's electric vehicles. Still needed are improvements in safety and durability, along with cost reductions. The current cost of lithium-ion batteries for vehicle applications is four to eight times that of lead acid batteries, and one to four times that of nickel metal hydride batteries (Nishino, 2010).

Although researchers at the University of Texas in Austin made crucial contributions to the development of the rechargeable lithium-ion battery in the 1980s, U.S. firms at that time declined to pursue the industry, leaving it to better established electronics companies in Japan. As a result, the United States for years had almost no presence in lithium-ion batteries. In the late 1990s, when Toyota raced ahead with the first hybrid vehicles, U.S. automakers belatedly learned the importance of acquiring relevant battery manufacturing capability.

The United States appears committed to learning from past experience and seizing the opportunity to be a leader in lithium-ion batteries for vehicles. U.S. firms have several advantages in lithium-ion batteries, including research capacity, a well-established domestic automotive industry, a large market for vehicles, and the support of government policies. According to announced capacity expansions, the United States is on track to achieve a 40%-share of global capacity to produce lithium-ion batteries for vehicles by 2015 (DOE, 2010). Funds from the American Reinvestment and Recovery Act of 2009 have jumpstarted the U.S. industry from only two battery pack plants pre-ARRA, to 30 planned sites, all playing key roles across the value chain, including materials, components, and production of cells and battery packs.

This report maps out the U.S. value chain of lithium-ion batteries for hybrid and all-electric vehicles and identifies the manufacturing that takes place in the United States. Our analysis yields the following key findings about the value chain:

- At least 50 U.S.-based firms are involved to date, with 119 locations in 27 states performing manufacturing and research and development (R&D).[1] California and Michigan have the most activity, with 28 and 13 sites, respectively. Other geographic areas of concentration include the Northeast Atlantic (9 sites), Greater Chicago area (8) and the Carolinas (7). In addition to these established firms, at least 18 U.S. startups are entering the industry.

- U.S. activity is concentrated in Tier 1 (cell/battery pack assembly), highlighting the need for increased domestic manufacture of cells and cell components. For firms that have or plan to have U.S. manufacturing locations, we identified 21 lithium-ion battery pack players relevant to automotive applications. Most of these firms import battery cells from non-U.S. suppliers and only perform final pack assembly in the United States. Currently, only EnerDel operates its own high-volume cell manufacturing facilities domestically (Deutsche Bank, 2009). With the help of funding from the Department of Energy (DOE), several companies are trying to establish vertically integrated cell-to-pack capacity, including A123, CPI, EnerDel, and JCI-Saft. The state of Michigan is aggressively attracting this activity, offering significant financial incentives.

- U.S.-based firms are working to increase their capabilities in cell production, which accounts for the highest value, or 45 percent of total input cost. The United States is already a major player in two out of the four major cell components (electrolyte and separator), but so far a minor player in cathodes and anodes. Ohio-based Novolyte is a global player in electrolytes, with over 30 years of experience supplying electrolytes to primary cells, rechargeable cells and ultracapacitors. In separators, North Carolina-based Celgard has a 20-30% share of the global market. In all, we found 29 firms making cell components and electronics in the United States, and five firms providing materials. Many of the estimated 18 U.S. venture capital startups are developing new types of cell components or final cell products.

- Two U.S. companies, Chemetall and FMC, together supply nearly 50% of the world's demand for lithium. Globally there are three main suppliers of lithium: FMC Lithium (based in Charlotte, NC with lithium holdings in Argentina and Chile), SQM (based in Chile), and Chemetall Foote Corp (based in Kings Mountain, NC). Chemetall sources

[1] Figures include existing and planned facilities. Manufacturing and R&D sites are counted separately, even though in some cases they may occur in the same location. Thus, the total number of unique locations is approximately 108.

lithium from Chile and from the only operating U.S. source of lithium raw materials, in Silver Peak, Nevada.

- Several items critical to cell production remain difficult to source domestically, and thus more U.S-based cell component and material suppliers are needed in order to capture higher value. Arkema is the sole U.S. producer of anode and cathode binder. Oak-Mitsui is the sole U.S. producer of copper foil for anodes. Recently, several large chemical firms have created new divisions to fill these gaps, including 3M, DuPont and Dow Kokam.

- U.S. firms are moving aggressively to catch up to the Asian giants in establishing high-speed, precision-controlled processing. Five Japanese and two Korean battery manufacturers are 10 years ahead in high-volume production of lithium-ion batteries (Farley, 2010). U.S. firms are filling holes in battery processing expertise via global mergers and acquisitions, including Ener1's purchase of Enertech, a large Korean battery maker, and the battery division of Delphi, an auto parts supplier. EnerDel has also hired a number of Asian battery engineers to expand their battery R&D (Deutsche Bank, 2009).

- Strategic joint ventures with non-U.S.-owned firms can play a critical role in the evolving U.S. value chain. The United States has scant experience in manufacturing lithium-ion batteries, so safety and validation are an essential step toward a ramp-up of the U.S. industry. GM chose South Korean firm LG Chem and its Troy, MI-based subsidiary Compact Power, Inc. to provide batteries for its Chevy Volt, very likely because no one in the United States would have been ready to supply in time for the car's release.

Our research highlights the following key features of the U.S. position in lithium-ion batteries:

- Although U.S. government support is substantial, private investment in the U.S. industry has lagged that of its Asian competitors. The "roadmaps" of the U.S. DOE and Japan's corresponding agency, New Energy and Industrial Technology Development Organization (NEDO), are very similar, and DOE's budget for lithium-ion battery development has in fact surpassed Japan's since 2006 (NEDO, 2009). The state of Michigan is also providing large incentives. However, when it comes to corporate funding for R&D, Asian firms in this sector, which are more numerous and better established, are likely outspending their U.S. counterparts.

- While the United States has outstanding lithium-ion battery research capabilities, it has lagged Japan in translating this knowledge into patented products. Of all lithium-ion-relevant research papers published worldwide between 1998 and 2007, the United States accounted for 18%, second only to Japan (22%). In lithium-ion battery patents, Japan dominated more clearly, accounting for 52% of patents filed in the United States and

52% of those filed internationally—while the United States was in a more distant second place, with only 21% and 22% of patents in each category, respectively (METI, 2009b).

- As in any new industry, it is extremely difficult to forecast the future market for electric vehicle batteries, and therefore equally difficult to plan future capacity in alignment with demand. Battery firms worldwide face this dilemma. Global industry projections indicate a period of overcapacity in 2012-2015, but they also point to an excess in demand soon thereafter, in 2015-2017, especially in Japan and the United States. While the risk of overcapacity is very real for U.S. firms, it may actually pale in comparison to the opposite risk: that of not being prepared to lead this new industry, with serious implications for the U.S. edge in the global automotive sector. This dilemma highlights the need to adopt a long-term perspective on lithium-ion battery manufacturing.

- The United States can play to its strengths and compete with Asian firms. Strengths and opportunities include R&D capabilities at national labs and universities, a jump start provided by federal and state funding, and the industry's projection that the largest share of electric vehicles in the near future will be made in the United States. To remain competitive, U.S. firms will need to bring down production costs through automation and maintain their innovative edge in R&D instead of playing catch-up on mass production.

- Lithium-ion battery development offers important synergies with other clean energy value chains. The reliability of solar and wind power can be enhanced by using lithium-ion energy storage to stabilize power production and to store energy for periods of no sun or wind. In vehicle-to-grid systems, batteries in electric vehicles can charge during non-peak hours (at night) and sell power back to the grid during peak hours (when vehicles are parked during the work day). If battery durability is improved, used EV batteries could potentially be re-purposed as home energy storage devices, selling power in peak hours and providing emergency power supply.

- Advances in nanomaterials for lithium-ion batteries will contribute to other areas of innovation, including fuel cells, electronics and biotechnology. The United States is a leader in nanotechnology development. U.S. chemical giants including DuPont, 3M and Dow Chemical, along with a number of startup companies, are using their nanotechnology expertise to enter the market for lithium-ion battery materials. If research institutions and private firms were to cooperate to move nanomaterials to the high-volume production stage, the benefits would accrue not just to lithium-ion battery technology but to many other industries.

Introduction

President William Taft (1909-1913) was the first U.S. President to own an automobile, a Baker Electric (Gorzelany, 2008). A century later, the United States is once again looking to electricity to power its vehicles. Reasons for switching from gasoline to electricity include reducing carbon emissions, cutting dependence on oil, and, in no small part, keeping and creating U.S. jobs. What an internal combustion engine is to a conventional car, a battery is to an electric car; thus, if the United States is to revive its auto sector, it will need battery-manufacturing capacity.

Lithium-ion (lithium-ion) batteries are projected to become the most popular battery for plug-in and full-battery electric vehicles (PHEVs and BEVs). While other types of batteries, including lead-acid and nickel-metal hydride (in the first generation of the Toyota Prius hybrid) will continue to retain considerable market share in the short term, lithium-ion batteries are expected to dominate the market by 2017 (Deutsche Bank, 2009). Compared with other relevant battery types, lithium-ion batteries have the highest power density. Their cost is rapidly decreasing.

It is important that battery manufacturing takes place near auto manufacturing. Beyond the difficulties of customs, transportation, shipping regulations and high shipping costs of heavy items, battery and electric vehicle manufacturing are inherently connected due to sharing in R&D and manufacturing facilities. Perhaps most important, automakers want agile and reliable suppliers nearby.

Because the United States eventually is projected to lead in the manufacture of electric vehicles, a domestic base of lithium-ion battery manufacturing capacity will be critical (Nishino, 2010). The U.S. battery industry will need to think long-term if it is to survive and thrive in the coming years within a fiercely competitive lithium-ion battery market. Our research addresses the following questions relevant to the U.S. trajectory:

- What are the main technology challenges?
- How is the United States positioned within the global market?
- How developed is the U.S. value chain?
- What does the future of U.S. battery manufacturing look like?
- What synergies are there between lithium-ion batteries and other clean energy value chains?

This report will map out the current U.S. value chain for lithium-ion batteries for hybrid and all-electric vehicles. It will identify the nature and extent of the manufacturing that is expected to take place in the United States in coming years as the electric vehicle industry continues to develop.

Technology basics

Battery performance requirements depend on the vehicle application. Two important factors determine battery performance: energy, which can be thought of as driving range, and power, which can be thought of as acceleration. The power-to-energy (P/E) ratio shows how much power per unit of energy is required for the application (DOE, 2007). Figure 1 shows how deeply batteries are charged (state of charge) when they are used in different applications.

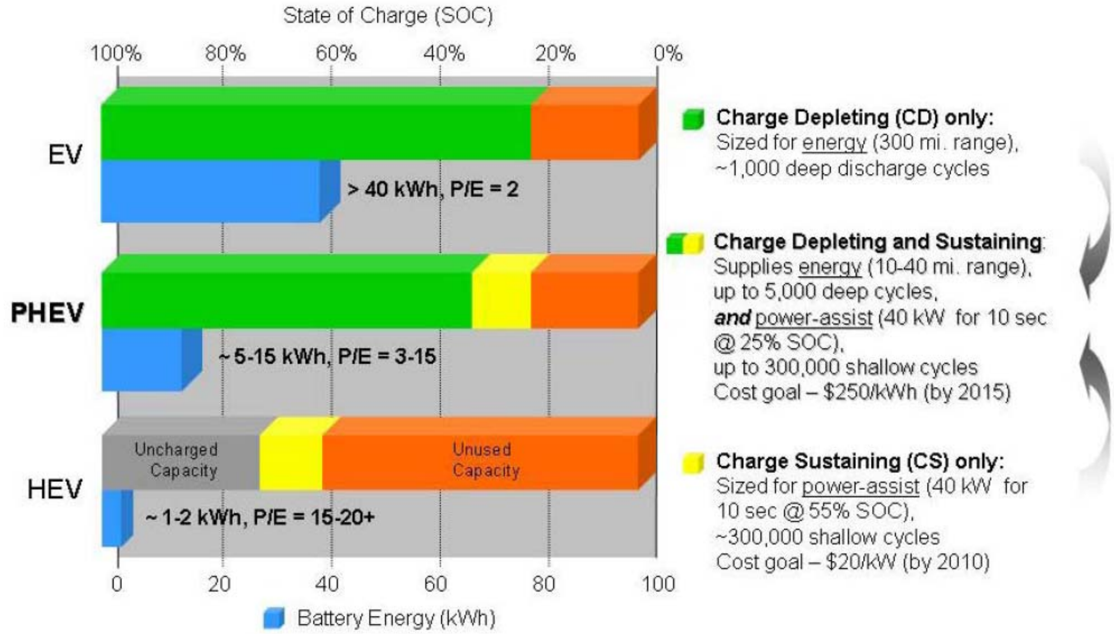
HEVs: Most HEVs use batteries to store energy captured during braking and use this energy to boost a vehicle's acceleration.[2] The battery in an HEV is required to store only a small amount of energy, since it is recharged frequently during driving. Batteries for HEVs have a "shallow cycle,"—which means they do not fully charge—and they are designed for a 300,000-cycle lifetime. Because of these cycle characteristics, HEV batteries need more power than energy, resulting in high P/E values ranging from 15 to 20. The battery capacity is relatively small, just 1-2 kilowatt-hours (kWh) (DOE, 2007).

PHEVs: PHEVs are hybrid vehicles with large-capacity batteries that can be charged from the electric grid. With their larger battery capacity, 5 to 15 kWh (DOE, 2007), PHEVs use only their electric motor and stored battery power to travel for short distances, meaning that PHEVs do not consume any liquid fossil fuels for short trips if the batteries are fully charged (Hori, 1998). After battery-stored energy is depleted, the battery works as an HEV battery for power assisting. Thus, a PHEV battery needs both energy and power performance, resulting in a medium P/E range of 3-15. In other words, PHEV batteries require both shallow cycle durability—similar to HEVs—and deep cycle durability.

EVs: EVs only use an electric motor powered by batteries to power the vehicle. Batteries for EVs need more energy capacity because of longer driving ranges, so EVs have the lowest P/E factor. The battery gets fully charged and discharged (deep cycles) and requires 1,000-cycle durability. The battery size of EVs is larger than that for PHEVs or HEVs. For example, the Nissan Leaf has a 24-kWh capacity (Nissan USA, 2010). Lithium-ion battery packs for compact EVs will use 1,800 to 2,000 cells (METI, 2009b).

[2] Another fuel-saving configuration is a micro-hybrid, in which the system stops the engine during idling and restarts it immediately when the vehicle begins to move (Deutsche Bank, 2009).

Figure 1. Battery performance requirement by vehicle application



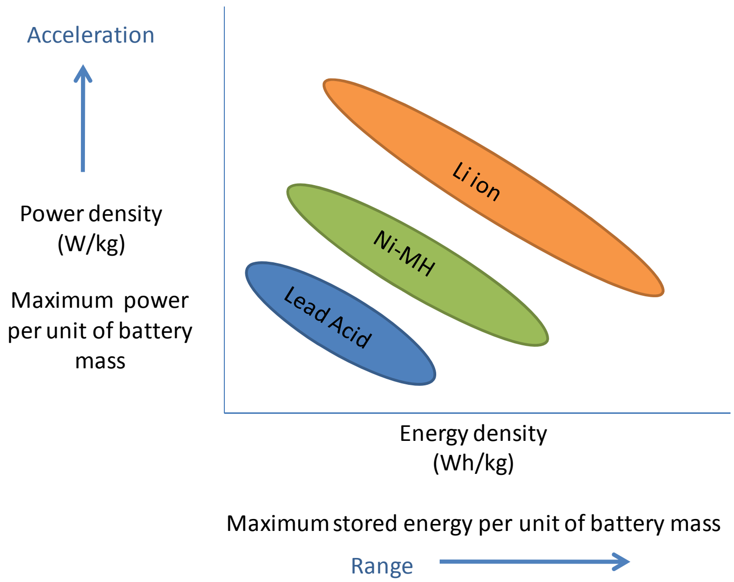
Source: (DOE, 2007)

Advantages of lithium-ion batteries for vehicle use

Lithium-ion batteries are the most suitable existing technology for electric vehicles because they can output high energy and power per unit of battery mass, allowing them to be lighter and smaller than other rechargeable batteries (see Figure 2). These features also explain why lithium-ion batteries are already widely used for consumer electronics such as cell phones, laptop computers, digital cameras/video cameras, and portable audio/game players. Other advantages of lithium-ion batteries compared to lead acid and nickel metal hydride batteries include high-energy efficiency, no memory effects,[3] and a relatively long cycle life (see Table 1).

[3] Memory effect in Ni-Cd batteries refers to a decrease in energy capacity after the battery has been discharged shallowly. The battery remembers the smaller capacity and thereafter can no longer charge fully. Lithium-ion batteries do not have this memory effect, so the battery can always be recharged even before its stored energy has been depleted (Yoshino, 2008).

Figure 2. Power (acceleration) and energy (range) by battery type



Source: CGGC based on (Abuelsamid, 2007)

Table 1. Technical performance by existing battery type

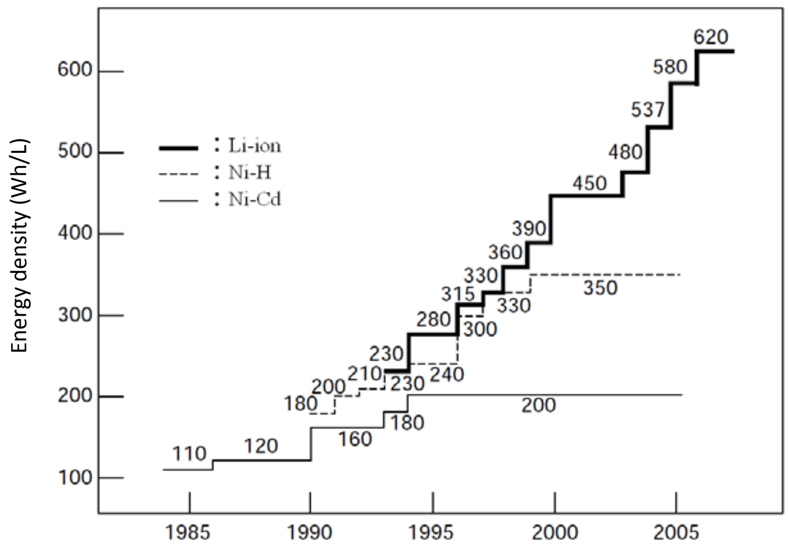
Battery type	Lead acid	Ni-Cd	Ni-MH	Lithium-ion
Energy density [a] (Wh/Kg)	35	40-60	60	120
Power density (W/kg)	180	150	250-1000	1,800
Cycle life [c]	4,500	2,000	2,000	3,500
Cost ($/kWh)[d]	269	280	500-1,000	Consumer electronics: 300-800 Vehicles: 1,000-2,000
Battery characteristics	High reliability, low cost	Memory effect	Currently, best value and most popular battery for HEVs	Small size, light weight
Application	Car battery, forklift, golf cart, backup power	Replacement for flashlight battery	HEVs, replacement for flashlight battery	Consumer electronics

a: Chargeable electric energy per weight of battery pack
b: Proportion of dischargeable electric energy to charged energy
c: The number of charging/discharging cycles in battery's entire life
d: Calculated exchange rate is $1= 92.99 yen (05/14/2010 – www.oanda.com). Ranges given are approximate.
e: Lithium-ion batteries for consumer electronics have lower costs than those for vehicle use because of high-volume production and a mature market.

Source: (Deutsche Bank, 2009; METI, 2009a; Nishino, 2010; The Institute of Applied Energy, 2008; Woodbank Communications Ltd, 2005)

Energy density: Lithium-ion batteries have a large potential to further increase energy density by using advanced anode and cathode materials. Lithium-ion batteries' energy density is increasing rapidly (see Figure 3). By contrast, the energy density of nickel cadmium (Ni-Cd) and nickel metal hydride (Ni-MH) batteries have flattened off since 1995 and 2000, respectively (METI, 2009a).

Figure 3. Advances in energy density of selected battery types, by year

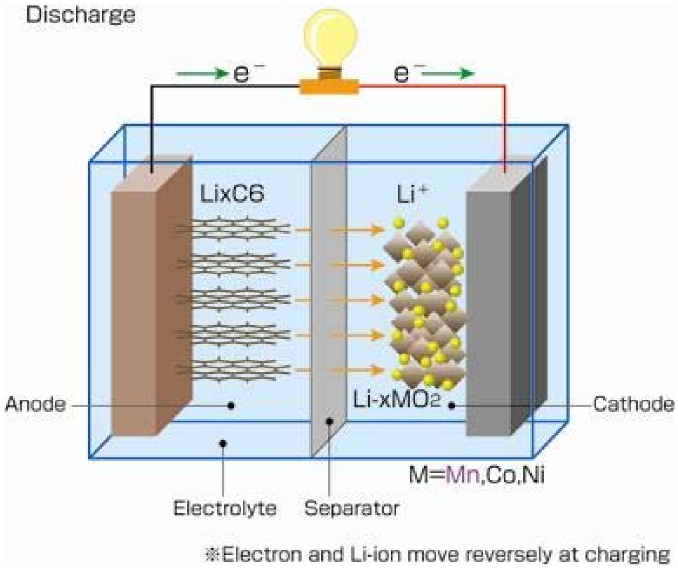


Source:(Ikoma, 2006)

How does a lithium-ion battery work?

A lithium-ion battery is a rechargeable battery in which lithium ions move between the anode and cathode, creating electricity flow useful for electronic applications. In the discharge cycle, lithium in the anode (carbon material) is ionized and emitted to the electrolyte. Lithium ions move through a porous plastic separator and insert into atomic-sized holes in the cathode (lithium metal oxide). At the same time, electrons are released from the anode. This becomes electric current traveling to an outside electric circuit (see Figure 4). When charging, lithium ions go from the cathode to the anode through the separator. Since this is a reversible chemical reaction, the battery can be recharged (Yoshino, 2008).

Figure 4. Discharging mechanism of a lithium-ion battery



Source: (Automotive Energy Supply Corporation, 2007)

A lithium-ion battery cell contains four main components: cathode, anode, electrolyte and separator. Table 2 shows the main components' functions and material compositions. Lithium-ion battery cells are sold in "battery packs," which include battery management systems (see Figure 5). A detailed description of each component will be shown in the U.S. Value Chain section.

Table 2. Lithium-ion battery components, functions, and main materials

Components	Functions	Materials
Cathode	• Emit lithium-ion to anode during charging • Receive lithium-ion during discharging	lithium metal oxide powder
Anode	• Receive lithium-ion from anode during charging • Emit lithium-ion during discharging	Graphite powder
Electrolyte	• Pass lithium-ions between cathode and anode	Lithium salts and organic solvents
Separator	• Prevent short circuit between cathode and anode • Pass lithium ions through pores in separator	Micro-porous membranes

Source: CGGC

Figure 5. Lithium-ion battery cell, module and pack

Source:(Hitachi Vehicle Energy, 2008; Magna, 2010)

Technology and cost challenges

Current battery performance of lithium-ion batteries is not sufficient to be widely used for HEVs, PHEVs, and EVs. In addition to necessary increases in energy and power density (performance), other improvements are needed in durability, safety, and cost.

Durability: Batteries in PHEVs and EVs are required to have reliable durability for deep cycles to keep longer life (The Institute of Applied Energy, 2008). Vehicle makers are aiming to develop lithium-ion batteries with a guaranteed five-year or 100,000 kilometer driving distance (Nishino, 2010). Deep cycles of lithium-ion battery decrease the battery capacity rapidly, but PHEVs and EVs will be charged after the battery-stored energy is almost depleted. In addition, the power of lithium-ion batteries decreases in cold weather. For use of electric vehicles in cold regions, further technology development will be necessary to overcome this problem.

Safety: Lithium-ion batteries are vulnerable to short-circuiting and overcharging. Lead acid, Ni-Cd and Ni-MH batteries perform safely even after short-circuiting and overcharging because they have low energy capacity and use inflammable electrolyte. However, when a lithium-ion battery short circuits, high electricity flows are created and the battery temperature increases to several hundred degrees within seconds, heating up neighboring cells and resulting in an entire battery combustion reaction (Jacoby, 2007). When lithium-ion batteries are unintentionally overcharged, the chemical structure of the anode and cathode are destroyed and some of the lithium ions form snowflake-shaped lithium metal deposits called "dendrites," which can cause the battery to short circuit or, in a worse-case scenario, explode and catch fire. Impurities in the lithium metal can also contaminate the batteries and cause the formation of dendrites, potentially causing short circuits and explosions (Buchmann, 2007). To prevent overcharging, lithium-ion batteries must be sold as battery packs with very precise voltage control systems. In other words, cells cannot simply be installed into a given electronic application. Even though lithium batteries have a number of safety measures (see U.S. Value Chain section, page 31), further safety measures need to be developed for vehicle use.

Cost: The high cost of lithium-ion batteries for vehicle use is a critical concern. According to the most recent estimates available for batteries for vehicle use, the cost of lithium-ion is four to eight times that of lead acid and one to four times that of NiMH (Nishino, 2010). However, the cost of lithium batteries is expected to decrease significantly because the batteries will be increasingly used for many applications, such as uninterruptible power supply (UPS), forklifts, consumer electronics and backup power supplies. As the market grows and production scales up, manufacturers will be able to enjoy economies of scale. According to Deutsche Bank, the cost of lithium-ion batteries will decrease from $650/kWh in 2009 to $325/kWh by 2020 (Deutsche Bank, 2009).

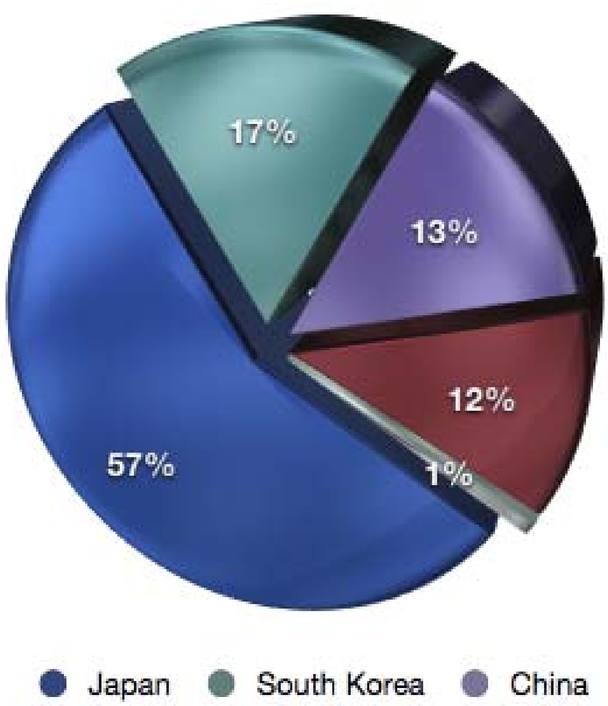
Global market

Demand for electric vehicle batteries is currently small, but it is expected to grow very quickly. In 2009, the global market for HEV and PHEV batteries was an estimated $1.3 billion (BCC Research, 2010). By 2020, the global market for advanced batteries for electric vehicles is expected to reach $25 billion—or about three times the size of today's entire lithium-ion battery market for consumer electronics (Boston Consulting Group, 2010).

China, Japan, South Korea, France, and the United States are the major lithium-ion battery manufacturers for hybrid and electric vehicle applications. Yet, due to several factors including a pre-existing electronics industry, Asia claims an overwhelming market share of lithium-ion battery manufacturing (see Figure 6 pie chart). In 2007, Japan held a 57% market share, Korea 17%, and China 13% (METI, 2010).

Japan's pole position is being threatened by Korean and Chinese companies who are rapidly increasing their market shares (NEDO, 2009). As recently as 2000, Korea and China only held 2% and 2.9% market shares respectively. As for the United States, only one company appears near the top (see Figure 1 table). A123Systems, Inc., with a one-percent world market share of lithium-ion batteries, ranks as the 14th largest lithium-ion battery manufacturer (NEDO, 2009).

Figure 6. Global lithium-ion battery market share, by country and by firm



1. Sanyo (Japan)	23%
2. Samsung (Korea)	15%
3. Sony (Japan)	14%
4. BYD (China)	8.3%
5. LG Chem (Korea)	7.4%
6. BAK (China)	6.6%
7. Panasonic (Japan)	6.0%
8. Hitachi Maxell (Japan)	5.3%
9. ATL (China)	3.8%
14. A123 Systems (U.S.)	**1%**

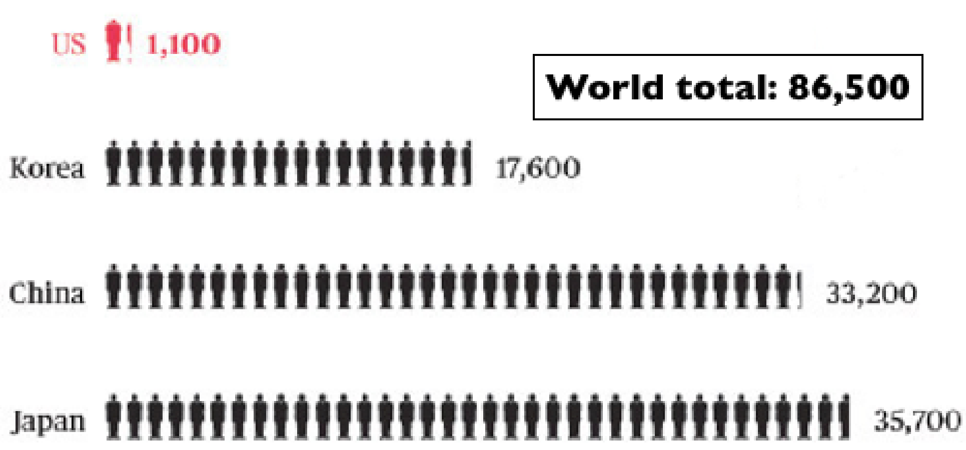
Source: CGGC, based on(METI, 2010; NEDO, 2009)

Calculating the global market share of lithium-ion batteries is inherently difficult, since lithium-ion batteries for consumer electronics and lithium-ion batteries for electric vehicles are two different markets. Currently, about 92% of lithium-ion batteries are for consumer use (METI, 2009b). However, this is projected to change as the popularity of electric vehicles gains traction.

Global market share numbers vary greatly depending on the source. According to one industry source, China currently has 40% and Japan 36% of the lithium-ion battery market. In 2008, the United States had an estimated 2% of the global advanced battery market for vehicles (Atkins, 2010). Recent numbers are consistent with Figure 6, but this is clearly a fast-changing market with Korea, China, and the United States all moving to grab market share away from Japan. 2009 figures rank market share holders as follows: Japan (56.3%), Korea (23.9%), China (12.3%), and Others (7.7%) (Asahi Shimbun, 2010).

Crucial cathode materials for the rechargeable lithium-ion battery were developed in the 1980s under the auspices of Professor John B. Goodenough at the University of Texas-Austin. However, control of the market eventually slipped away to Japan, and then spread to Korea and China. Japanese companies such as Sony Corp. and Panasonic Corp. were able to build a stronger manufacturing base for lithium-ion batteries because of significant demand from an already established electronics industry. Because of this demand, U.S. companies were disinclined to pursue R&D in the field, instead leaving it to better established and vertically integrated companies in Japan (Davis, 2010). China and South Korea soon followed Japan's lead and scaled up low-cost operations with which U.S. companies such as Duracell and Eveready could not compete (Lee, 2010). Today the jobs are accordingly located overwhelmingly in Asia (see Figure 7).

Figure 7. Global employment in the lithium-ion battery industry



Source: (Grove, 2010)

Eager to learn from past mistakes, the Obama administration has sought to foster lithium-ion manufacturing in the United States by distributing $2.4 billion in support. Conventional wisdom has considered manufacturing capacity moving abroad to be a negligible concern. However, this line of thinking has been questioned of late as unemployment soared, not to mention that manufacturing hubs often act as magnets for associated R&D. For example, when A123Systems got its start and began to look for funding, it attracted scant interest from the U.S. investment community, which has traditionally focused on funding innovation instead of domestic manufacturing (Lee, 2010). This led A123 to move its manufacturing capacity abroad, with jobs and intellectual property in tow.

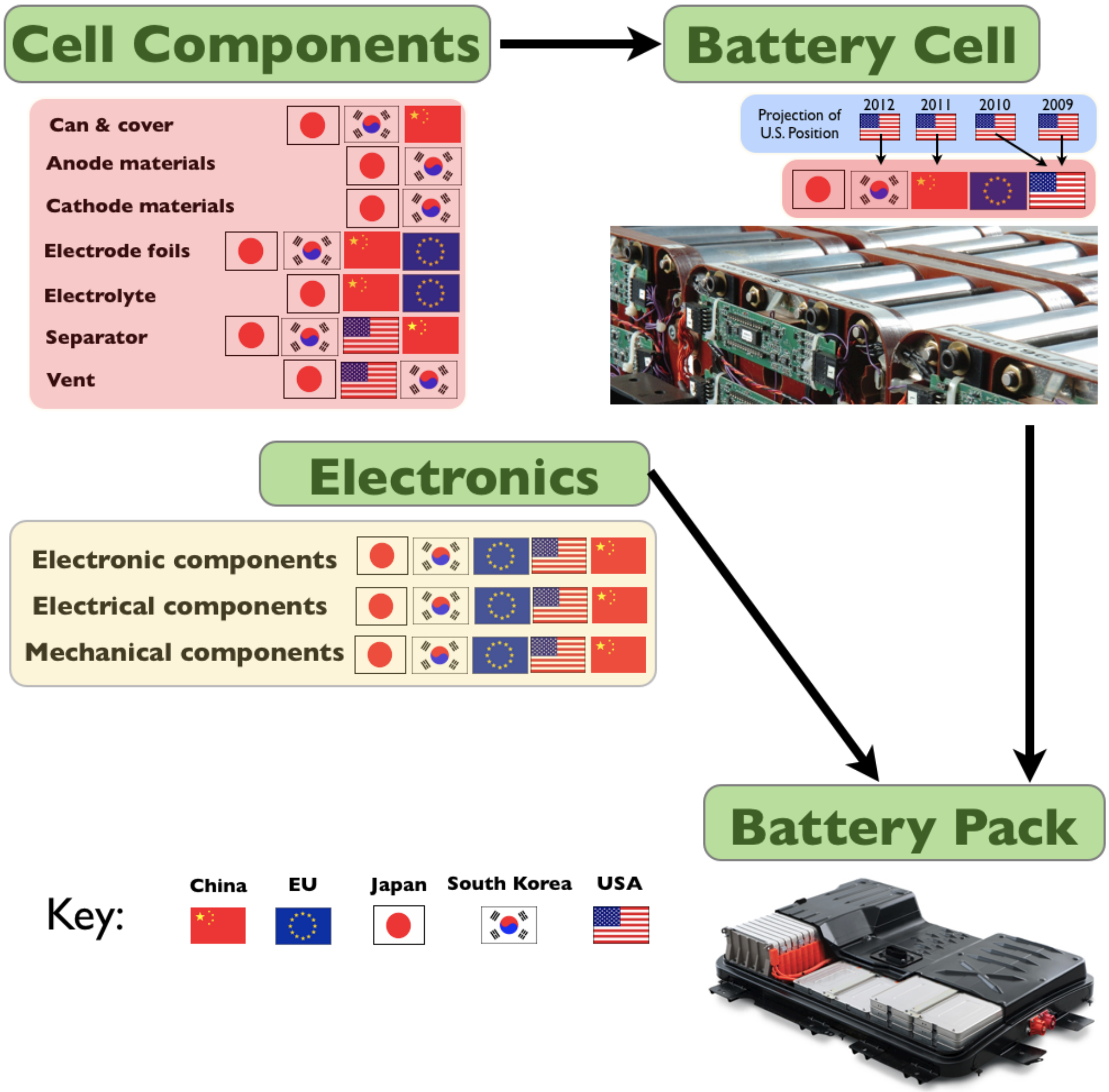
Worldwide, the United States is already a major player in two out of the four major cell components (electrolyte and separator). Ohio-based Novolyte is a global player in electrolytes, with over 30 years of experience supplying electrolytes to primary cells, rechargeable cells and ultracapacitors. In separators, North Carolina-based Celgard is one of the top three lithium battery separator providers, with an estimated global market share of 20-30%.[4]

However, in cathodes and anodes, the United States to date is a smaller player. According to Japan's government industrial technology development organization (NEDO), the global supply chain is dominated by Japanese companies in every major component category (see Figure 8). Relative shares are cited as follows: cathodes (73% Japanese market share), anodes (84%), electrolyte solutions (80%), and separators (71%) (NEDO, 2009).

As Figure 8 demonstrates, in lithium-ion batteries for electric vehicles, the United States is more involved in battery pack assembly than in cell manufacturing. Besides Novolyte in the electrolyte category and Celgard in the separator category, the United States lacks a significant presence in cell manufacturing. Japan is predominant in almost every category. China is also heavily involved in cell manufacturing, but, with the exception of Shenzhen-based automaker BYD, lacks a significant presence in battery pack assembly for electric vehicles. This can be partly attributed to the fact that battery pack assembly is done close to the end-use market due to the high cost of shipping batteries, which on average weigh 400-600 pounds. However, Chinese startups are cropping up rapidly and may soon establish themselves as a major player. Because the market is fairly new, the country rankings in Figure 8 may shift quickly, especially once sales of the Nissan Leaf and Chevy Volt begin in the United States.

[4] Polypore International SEC filing March 8, 2010. Estimated 20% figure is from (Nihon Securities Journal, 2009). Estimated 30% figure is from industry sources.

Figure 8. Lithium-ion cell & battery manufacturing, market share, by country



Source: CGGC and (Davis, 2010; Dunn, 2010; Ellerman, 2010). Images:(Abuelsamid, 2007; Argonne National Laboratory, 2010; inhabitat, 2010)

For now, the lithium-ion battery industry is overwhelmingly supplying the electronics market, including cell phones, personal computers, and digital/video cameras (NEDO, 2010). Lithium-ion batteries for vehicle use constitute a very new market. Current sales of lithium-ion batteries for electrics vehicles (EVs) and hybrid electrics vehicles (HEVs) only began in 2009 (Electro-to-Auto Forum, 2009).

Currently, two Japanese companies (Automotive Energy Supply Corp. and Hitachi) are producing lithium-ion batteries for HEVs and three others are setting up production (Toshiba, Sanyo[5] and Blue Energy, formerly a GS Yuasa/Honda joint venture) (Electro-to-Auto Forum, 2009). Two Japanese companies (Automotive Energy Supply Corp. and Lithium Energy Japan, a GS Yuasa/Mitsubishi joint venture) are producing lithium-ion batteries for EVs (Electro-to-Auto Forum, 2009). Because there is no existing capacity for volume production of lithium-ion batteries for vehicle use in the United States, Korea and Japan are moving to supply batteries for U.S. EV makers. Hitachi (Japan) plans to supply batteries to General Motors (GM) in late 2010 for a hybrid (Electro to Auto Forum, 2009).

National policies

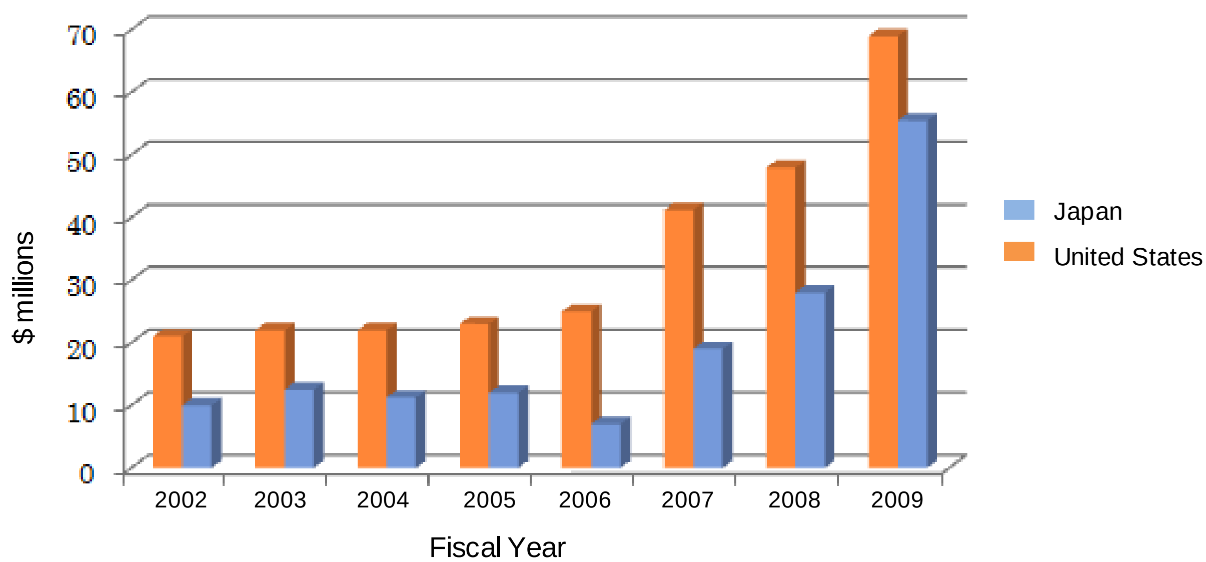
Japan, South Korea and China are pouring considerable funding into building a competitive supply chain of lithium-ion batteries for vehicles. Interestingly, demand for these batteries in China does not primarily stem from automotive applications, but electric bikes,[6] which have boosted vehicle battery demand and now constitute the largest transportation-related application in China (Freedonia, 2010).

Among the lead countries, public investment differs greatly. Although the "roadmaps" of the U.S. DOE and Japan's corresponding agency, NEDO, are very similar, DOE's budget for lithium-ion battery development has surpassed Japan's each year since 2002 (See Figure 9). This newly acquired edge stems from the American Reinvestment and Recovery Act (ARRA) as well as DOE's Advanced Battery Manufacturing Initiative. However, because Asian companies are better established, more corporate funds are being devoted to R&D compared to U.S. companies. Other governments have taken note of DOE's funding and are following suit.

[5] Sanyo merged with Panasonic in 2009.

[6] Primarily lead-acid batteries.

Figure 9. Government funding of battery technology development for vehicles, United States and Japan, 2002-2009



Note: Funding levels are approximate.

Sources: (Banerjee, 2010; NEDO, 2009)

Patents and R&D

The number of patents filed is an important measure that can be used to determine the international competitiveness of the United States in lithium-ion battery manufacturing. The number of technical papers published is similarly useful for measuring competitiveness in lithium-ion battery R&D. New material inventions for cathodes, anodes, electrolytes, separators, battery design and systems are included in this key research.

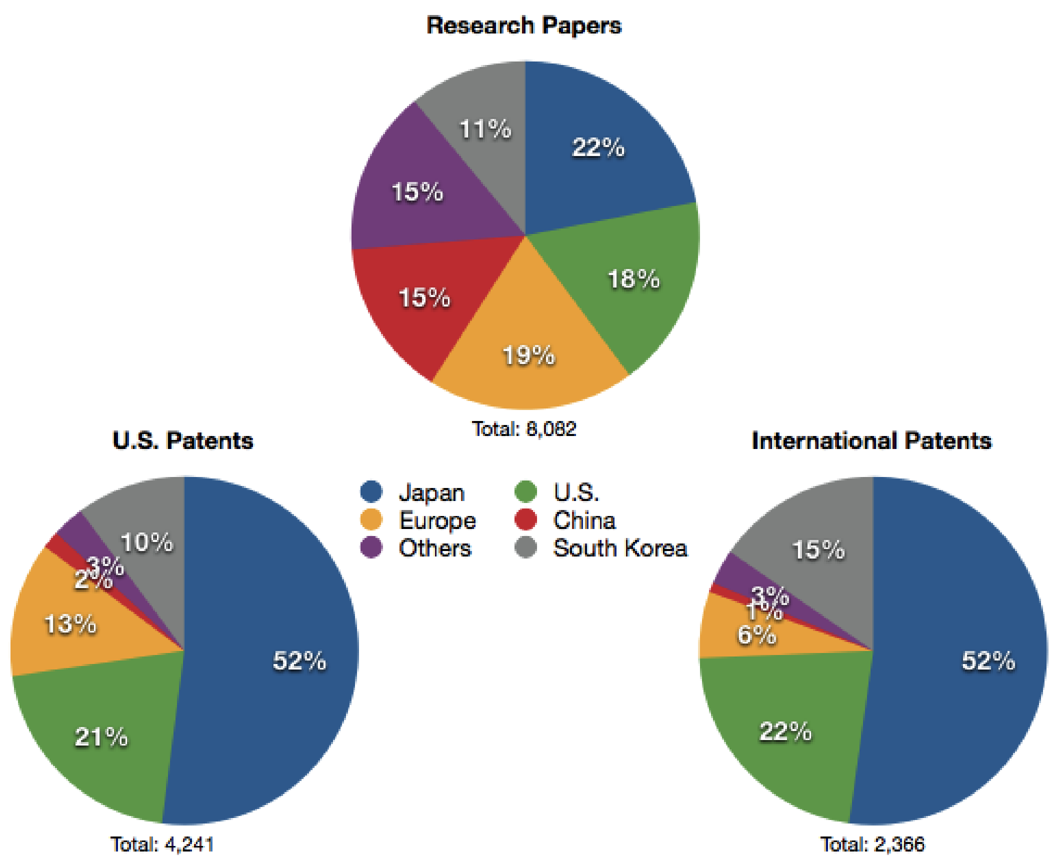
Japan is not only leading in the manufacture of lithium-ion batteries, but also in R&D. The United States ranks second to Japan for international and U.S. patents[7] related to lithium-ion batteries, about on par with other major players in publishing academic research papers (see Figure 10). The United States accounts for 22% of international patents and 21% of patents filed in the United States. Japan accounts for the largest proportion of patents filed in the United States (52%) and internationally (52%). In fact, for hybrid cars, Japan's Toyota alone filed an astounding 43% of all patent filings (Lloyd & Blows, 2009). Korea is not far behind and

[7] International patents are patents applied to the Patent Cooperation Treaty (PCT), an international patent law treaty, from 1998 to 2007 (METI, 2009b). U.S. patents are patents to the U.S. Patent and Trademark Office (PTO) from 1998 to 2007 (METI, 2009b)

increased its proportion of lithium-ion battery patents filed in the United States from 11% in 1998-2001 to 20% in 2005-2007 (METI, 2009b).

Only three U.S. companies, Greatbatch, Valence Technology, and 3M, are in the top 10 U.S. patent applicants for lithium-ion batteries (see Table 3).[8] In terms of research papers,[9] Japan does not dominate as it does in patents (see Table 4). U.S. research institutes in the lead include Argonne National Laboratory, Lawrence Berkeley National Laboratory, University of California, and Massachusetts Institute of Technology. Together, the figures suggest that the United States has significant abilities in lithium-ion battery R&D, but has not yet accumulated the know-how to commercialize and scale-up the relevant technologies.

Figure 10. Patents and research papers related to lithium-ion batteries 1998 – 2007, by country



Source: (METI, 2009b).

[8] These include patents for non-automotive applications.

[9] Research papers include 46 academic papers in journals such as Journal of Power Sources, Journal of Physical Chemistry, Chemistry of Materials, Nature and Science (METI, 2009b).

Table 3. Top 10 applicants for lithium-ion battery patents in the United States

Rank	Applicant name	Country	Application number
1	Samsung SDI	South Korea	415
2	Panasonic	Japan	375
3	Sony	Japan	328
4	Sanyo	Japan	312
5	LG Chem	South Korea	120
6	Toshiba	Japan	92
7	**Greatbatch**	**USA**	**77**
8	**Valence Technology**	**USA**	**76**
9	Mitsubishi Chemistry	Japan	73
10	**3M**	**USA**	**60**
		Total patents	**1,928**

Source: (METI, 2009b)

Table 4. Top 30 authors of academic research papers related to lithium-ion batteries

Rank	Name of organization	Country	Number of papers
1	AIST (National Institute of Advanced Industrial Science And Technology)	Japan	368
2	Kyoto University	Japan	280
3	The Chinese Academy of Sciences	China	267
4	Tokyo Institute of Technology	Japan	255
5	**Argonne National Laboratory**	**USA**	**241**
6	Hanyang University	Korea	210
7	Kyusyu University	Japan	169
8	Saga University	Japan	168
9	Fudan University	China	158
10	Seoul National University	Korea	157
11	Dalhousie University	Canada	152
12	CNRS	France	148
13	Université De Picardie Jules Verne	France	142
13	KAIST (Korea Advanced Institute of Science And Technology)	Korea	142
15	Cordoba University	Spain	141
16	**University of California**	**USA**	**139**
17	GS Yuasa	Japan	134
17	**Lawrence Berkeley National Laboratory**	**USA**	**134**

Rank	Name of organization	Country	Number of papers
19	Università Degli Studi Di Roma	Italy	133
19	Tokyo University of Science	Japan	133
21	National University of Singapore	Singapore	131
21	Tsinghua University	China	131
23	Iwate University	Japan	130
24	University of Wollongong	Australia	121
24	**Massachusetts Institute of Technology**	**USA**	**121**
26	Wuhan University	China	119
26	KIST (Korea Institute of Science And Technology)	Korea	119
28	Bar-Ilan University	Israel	118
29	Université Pierre Et Marie Curie	France	117
30	Tohoku University	Japan	113

Source: (METI, 2009b)

Lead battery pack firms

Lead firms in the United States are trying to capture more of the value in the lithium-ion battery value chain through domestic manufacturing. Indeed, this was the main objective of recent DOE funding. Several companies are seeking to establish vertically integrated cell-to-pack capacity in the United States, including A123, CPI, EnerDel, and JCI-Saft. Michigan has been the focal point of much of this activity: of the $2.4 billion awarded in ARRA, Michigan got about half. The state of Michigan also has been very proactive in attracting battery companies with incentives such as tax benefits. For example, tax cuts were given to LG Chem on the order of $130 million, which together with the $151 million granted by the DOE almost entirely covered LG Chem's construction costs for a new facility. Michigan now ranks third for clean energy patents in the nation (Goodell & Daining, 2010).

Although much industry and media attention has focused on lithium-ion battery manufacturing, currently there is no volume production in the United States. Table 5 lists the major battery pack firms, including those with U.S. and non-U.S. manufacturing locations. Among them, LG Chem recently broke ground on a $303 million, 650,000-square-foot battery cell production facility in Holland, Michigan through its U.S. subsidiary, Compact Power, Inc. (CPI). CPI recently won important contracts to supply batteries for the Ford Focus PHEV, and for the Chevy Volt over A123Systems. Until 2012, these batteries will be imported from LG Chem in Korea, but it is expected that thereafter, the U.S. plant will be capable of volume production of cells, including those for the Volt. By 2013, the U.S. plant will assemble 200,000 battery packs per year and employ 400 people (Goodell & Daining, 2010).

One of the leading battery assemblers is Johnson Controls Inc., which has a joint venture with French battery manufacturer Saft since 2006 and is setting up a $220-million plant in Holland, Michigan. The plant is projected to employ roughly 300 people and produce 10-15 million battery cells per year (Goodell & Daining, 2010; Mick, 2010). Together, these firms have experience in battery manufacturing for defense and space applications, and their joint venture (Johnson Controls-Saft Advanced Power Solutions) has been selected to supply lithium-ion batteries for a Daimler product, the Mercedes S Class 400 hybrid (Johnson Controls Inc., 2010).

A123 is constructing three plants in Michigan including a 3-MWh plant, which will be funded through a $249 million DOE grant along with a $235 million DOE loan, as well as $22 million in state and local government grants, to be matched with $308 million of A123 funds. The plant will have the capacity to produce approximately 120,000 EV battery packs per year, equivalent to 1.5 million HEV packs per year. Once the plant is operational, revenue will range from an estimated $2.25 to $2.75 billion per year (Deutsche Bank, 2009).

Also involved is GM, whose Brownstown, Michigan battery assembly plant has begun production for the Chevy Volt PHEV (Mick, 2010).

EnerDel (based in Indianapolis, IN) stands out as the only U.S. manufacturer of commercial-scale lithium-ion batteries for automotive applications; however, production has been limited to small quantities to date (EnerDel, 2010). EnerDel was formed in 2004 through partnerships between Ener1, Delphi Corporation, and Itochu Corporation and recently entered into a joint venture with China's largest auto-parts producer, Wanxiang (Hayden, 2010). For its part, Delphi Automotive got $89 million from DOE to develop EV components out of a Kokomo, Indiana facility (Mick, 2010). Dow Kokam broke ground in June, 2010, in Midland, Michigan, on a $600- million, 800,000-square-foot plant projected to employ roughly 700 people (Goodell & Daining, 2010).

Ultimately, the market will be decided by technology and experience. A long validation period is needed for any consumer product, especially a new product such as an electric car. The United States has scant experience in manufacturing lithium-ion batteries and therefore safety and validation are essential before ramping up can take place. It is likely that GM chose South Korean firm LG Chem and its Troy, MI-based subsidiary Compact Power, Inc. because no one in the United States would be ready to supply in time for the release of the Volt.

Table 5. Key players' production capacity for lithium-ion batteries: Europe, Japan, South Korea, United States

Company	Ownership: Key auto company	Ownership: Battery Company	Factory Location	Investment ($MM)	Capacity (EV-equivalent Units)	
					2010E	2015E
Ener1		Ener1 100%	Korea	20	15,000	15,000
			USA	600	30,000	120,000
Lithium Energy Japan	Mitsubishi 15%	GS-Yuasa 51%, Mitsubishi 34%	Japan	187	21,000	55,000
Blue Energy	Honda 49%	GS-Yuasa 51%	Japan	263	20,000	30,000
Panasonic EV Energy	Toyota 60%	Panasonic 40%	Japan (Li-ion)	111	9,400	9,400
AESC	Nissan 51%	NEC Group 49%	Japan	145	50,000	65,000
			USA	1000	0	200,000
			UK	330	0	60,000
			Spain	356	0	60,000
A123		A123 100%	USA	800	0	120,000
			Korea/China	0	15,000	15,000
Dow / Kokam	Dow	Kokam America	USA	350	0	60,000
JCI Saft	JCI 51%	Saft 49%	USA	600	0	140,000
Sanyo		Sanyo 100%	Japan (Li-ion)	315	2,000	110,000
Hitachi Vehicle Energy		Hitachi S / S 65%, Shinkobe 25%, Maxell 10%	Japan	456	10,000	70,000
Toshiba		Toshiba 100%	Japan	278	0	60,000
SB LiMotive*	Bosch 50%	Samsung 50%	S-Korea	500	0	149,000
LG Chem*		LG 100%	S-Korea		0	111,000
			USA	300		
SK Energy *		SK 100%	S-Korea	113	0	25,000
LiTec*	Daimler 49% Daimler 90%	Evonik-Degussa 51% (cells) Evonik-Degussa 10% (pack)	Germany	100	0	40,000
Total				6,824	172,000	1,514,000
			Average annual growth rate (2010-2015)			54%
			X times			8.8

Notes: * Base capacity estimate made by DB team

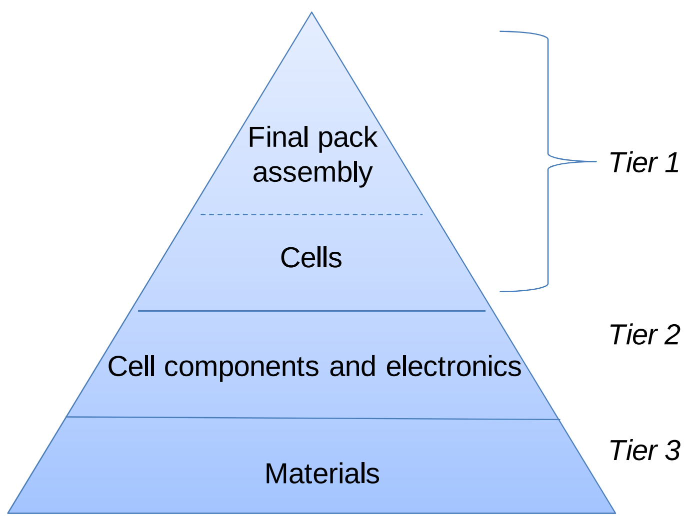
Note: Panasonic EV Energy is now Primearth EV Energy Corp. Sanyo has been bought by Panasonic Corp.

Source: (Deutsche Bank, 2009).

U.S. value chain

Figure 11 shows the general structure of the lithium-ion battery industry as a pyramid. Tier 1 consists of two activities, final pack assembly and cell manufacturing. Focusing on firms that have or plan to have U.S. manufacturing locations, our research identified 21 lithium-ion battery cell/pack players. Tier 2 consists of cell components and electronics. We identified 29 Tier 2 firms, including some OEMs that provide their own cell components. Tier 3 comprises key materials, and our research identified five Tier 3 firms with U.S. locations. In addition, we identified 18 U.S. venture capital startups developing next generation lithium-ion batteries, and one U.S. firm recycling materials.

Figure 11. Production structure of the lithium-ion battery industry



Source: CGGC

What goes into a battery?

To understand the value chain, it is useful first to know what a battery consists of. The heart of the battery is the cell, which is composed of four main features—cathode, anode, electrolyte and separator—along with a fifth category, safety structures. Each of these five components is described below.

1) Cathode. Cathodes are made of cathode materials pasted on aluminum foil. Cathode paste contains cathode materials, including lithium metal oxide, a binder (poly vinylidene fluoride (PVDF)), carbon material (carbon black, graphite powder, and carbon fiber, etc.) and solvent (N-methyl-2-pyrrolidone (NMP)). The paste is coated on aluminum foil, then dried and pressed into the appropriate thickness (METI, 2009b).

Four types of cathodes are used in lithium-ion batteries for vehicles. LMO (lithium manganese oxide) is the most commonly used as a cathode for HEVs, PHEVs, and EVs (See Table 6). Originally, LCO (lithium cobalt oxide) was commonly used in lithium-ion batteries for consumer electronics such as laptop PCs, cell phones, and cameras, due to its high energy density.[10] However, because of recent price increases in cobalt metal and safety issues[11] related to LCO cathodes, battery makers have opted for cheaper and safer alternatives, including LMO (lithium manganese oxide) and LFP (lithium iron phosphate) for vehicle use. NCA (nickel cobalt aluminum) and NMC (nickel manganese cobalt) are being aggressively developed because of their relatively high energy density.

Table 6. Four major types of cathodes for lithium-ion batteries: energy density, pros and cons, and manufacturers

Chemistry	Wh/Kg	Positives	Negatives	Makers
NCA (Nickel / Cobalt / Alum)	160	Energy density Power	Safety Cost / commodity exposure Life Expectancy Range of Charge	JCI/Saft PEVE AESC
LMO (Lithium Manganese Oxide)	150	Cost Safety Power	Life Expectancy Usable energy	Hitachi, AESC, Sanyo GS Yuasa, LG Chem Samsung, Toshiba Ener1, SK Corp, Altairnano
NMC (Nickel Manganese Cobalt)	150	Energy density Range of Charge	Safety (better than NCA) Cost / commodity exposure	PEVE, Hitachi, Sanyo LG Chem, Samsung Ener1, Evonik, GS Yuasa
LFP (Lithium Iron Phosphate)	140	Safety Life Expectancy Range of Charge Material Cost	Low temp performance Processing costs	A123, BYD GS Yuasa, JCI/Saft Valence, Lishen

Source: (Deutsche Bank, 2009)

<u>2) Anode</u>. Anodes are made of anode materials pasted on copper foil. Anode active materials, such as graphite, are kneaded with binder (PVDF or styrene butadiene rubber (SBR)), solvent (NMP or water), and carbon (carbon tubes and carbon black) (METI, 2009b). After coating, the anode is dried and pressed. Two types of anode active material are primarily used: highly crystallized natural graphite and randomly crystallized artificial carbon.

<u>3) Electrolyte</u>. Electrolyte used in lithium-ion batteries is a mixture of lithium salt and organic solvent. Several organic solvents are mixed to decrease the electrolyte's viscosity and increase solubility of lithium salts (METI, 2009b). This increases the mobility of lithium ions in the

[10] Theoretical energy density of lithium cobalt oxide is 570 Wh/kg. Lithium manganese oxide and lithium iron phosphate have 400 Wh/kg and 544 Wh/kg, respectively (NEDO, 2009).

[11] NCA tends to induce a battery explosion more than other cathode materials because NCA is thermally unstable (Buchmann, 2007).

electrolyte, resulting in higher battery performance. Lithium polymer batteries use gel electrolyte to prevent electrolyte from leaking from the laminate pouch. Gel electrolyte is composed of electrolyte with an added gel precursor. The materials below are used for making electrolyte.

Materials used as lithium salts:

- Lithium hexafluorophosphate ($LiPF_6$)
- Lithium perchlorate ($LiClO_4$)
- Lithium hexafluoroarsenate ($LiAsF_6$)

Organic solvents:

- Ethyl methyl carbonate (EMC)
- Dimethyl carbonate (DMC)
- Diethyl carbonate (DEC)
- Propylene carbonate (PC)
- Ethylene carbonate (EC)

Materials used to create gel electrolyte (for lithium polymer battery):

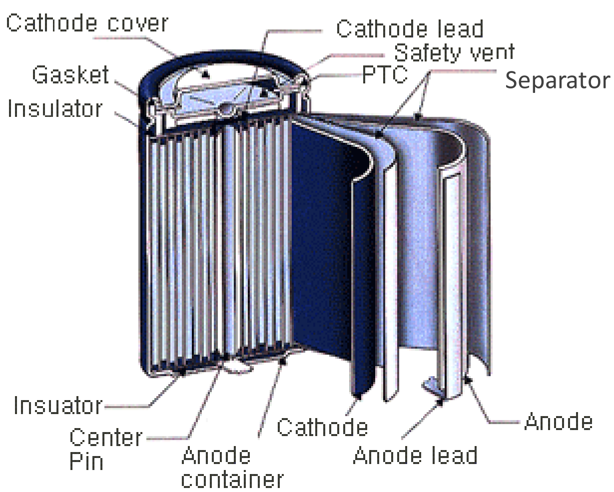
- Polyethylene oxide (PEO)
- Polyacrylonitrile (PAN)
- Poly vinylidene fluoride (PVDF)
- Poly methyl methacrylate (PMMA)

4) Separator. The separator is a micro-porous membrane, which prevents contact between the anode and cathode. The separator is made of either polyethylene or polypropylene. In addition, the separator has a safety function called a “shutdown.” If the cell heats up accidentally, the separator melts due to the high temperature and fills its micro pores to stop lithium-ion flow between anode and cathode (METI, 2009b).

5) Safety structures. Lithium-ion batteries have internal safety structures, such as tear-away tabs to reduce internal pressure, safety vents for air pressure relief, and thermal interrupters called positive temperature coefficient (PTC) thermistors, for overcurrent protection (Gold Peak Industries, 2000; Yoshino, 2008). Some battery companies insert a metal center pin as a pillar to strengthen against bending force and put insulators on the edge of the electrode where short circuit accidents are likely to generate.

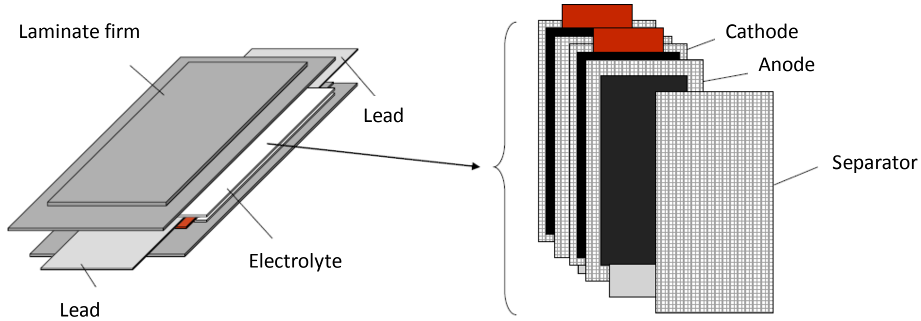
Lithium-ion battery cells come in two types of packaging: metal cans (cylindrical or prismatic cans) or laminate film (stack cells, lithium-ion polymer battery) (Alternative Energy Today, 2008). Lithium-ion battery cells are structured into three primary layers consisting of the cathode, anode and separator. In a cylindrical case, these layers are rolled and sealed in metal cans with electrolyte (see Figure 12). In a stacked configuration, the three layers are enclosed in laminate film and their edges are heat-sealed (see Figure 13). The stacked case often uses gel to prevent electrolyte from leaking. The voltage, energy capacity, power, life, and safety of a lithium-ion battery can be changed significantly by material choice, as explained below.

Figure 12. Structure of a cylindrical lithium-ion battery



Source: (GM-Volt, 2008)

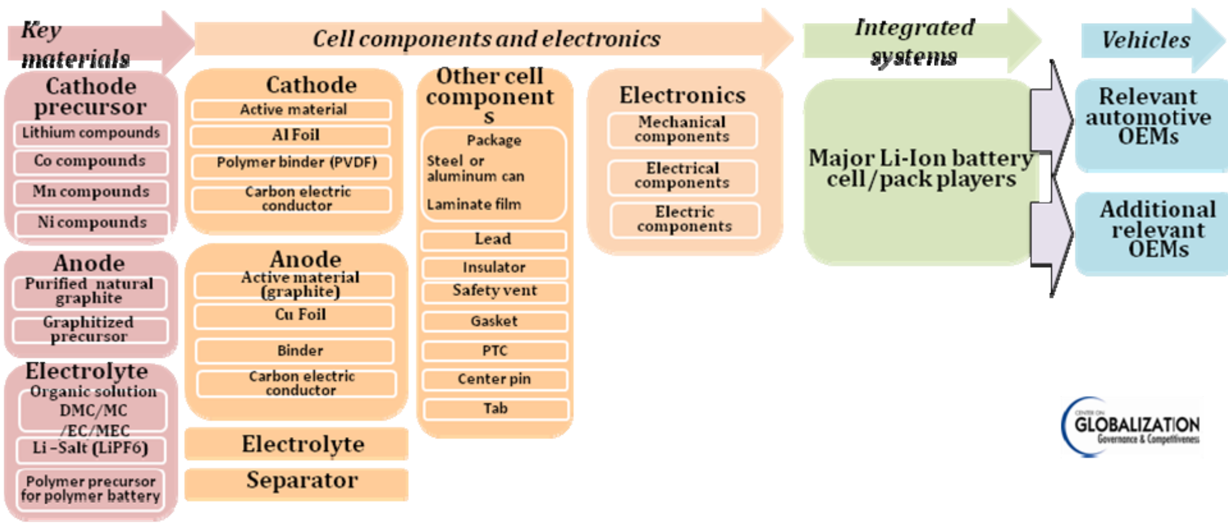
Figure 13. Structure of a stack lithium-ion battery



Source: (Kishida et al., 2004)

The value chain of the lithium-ion battery industry for vehicle use is found in Figure 14. Beginning with the first column on the left, key materials include cathode precursors (lithium, cobalt, nickel, manganese), anodes (graphite precursor or natural graphite), and electrolyte materials (organic solution, lithium salt, and polymer precursor for polymer batteries). The cell components and electronics segment consists of suppliers of main parts that go into battery cells and electronics for battery packs. Electronics include mechanical components (cooling systems, fasteners, packaging), electrical components (electric cables and connectors), and electronic components (chipsets for the battery management system). The final column of the chain contains relevant automotive OEMs, which manufacture vehicles using battery systems.

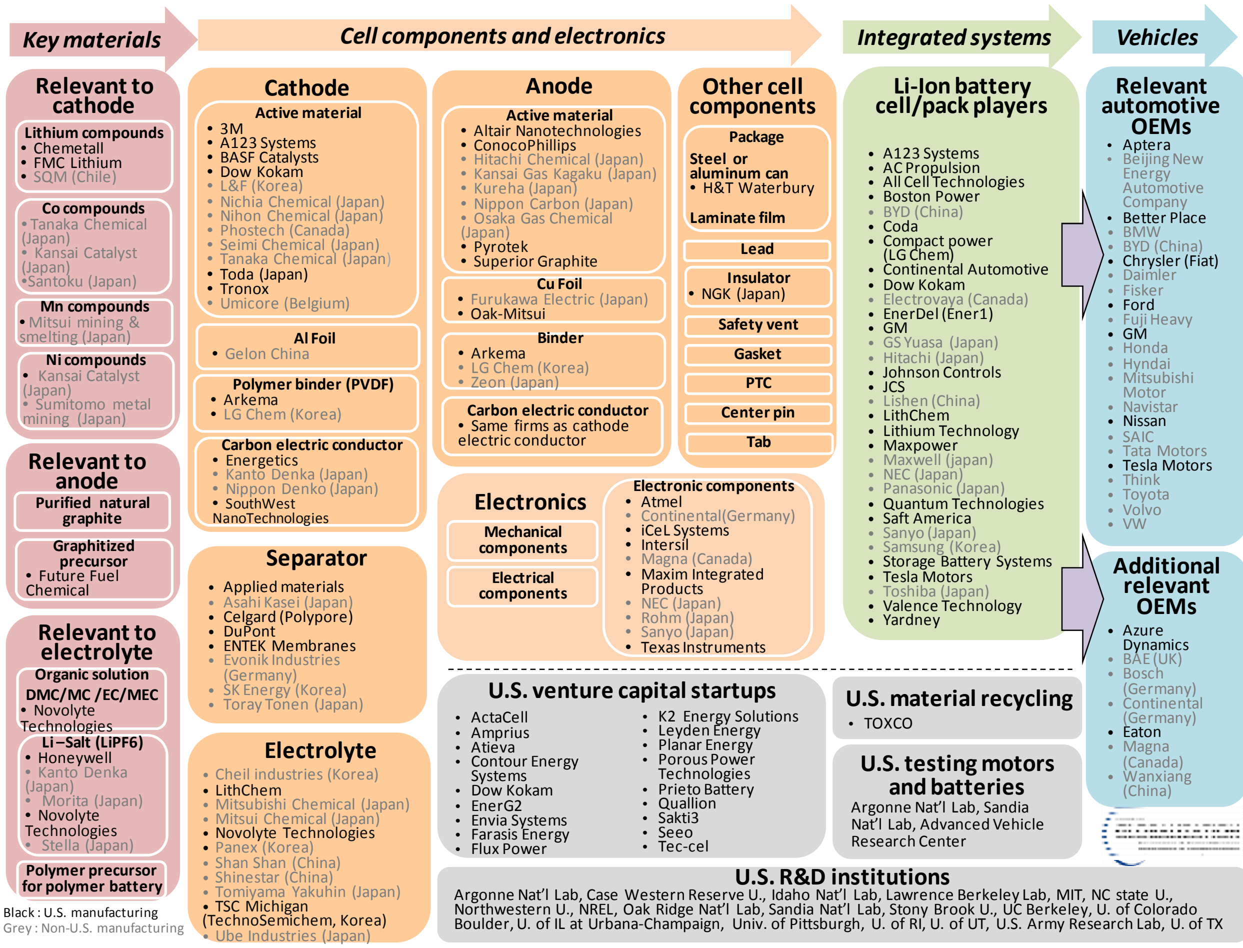
Figure 14. Value chain of lithium-ion batteries for vehicles



Source: CGGC

Figure 15 shows a more detailed value chain depicting major global and U.S. players in the manufacture of lithium-ion batteries for vehicles. Firms in black font have U.S. manufacturing locations, while those in grey are global players without U.S. manufacturing locations. Included in this value chain diagram are U.S. venture capital startups that are developing new types of cell components and final cell products. Also included are material recycling companies that are primarily recycling precious metals in lithium-ion batteries, such as lithium and cobalt.

Figure 15. Global value chain of lithium-ion batteries for vehicles, with major global players and U.S. players with current and planned facilities (not exhaustive)



Note: U.S. companies include those with planned as well as existing facilities.

Source: CGGC, based on company websites and industry interviews.

U.S. value chain, by segment

This section will describe each part of the value chain in detail.

Key materials. In the area of lithium compounds, which are key materials used as cathode precursors, the United States holds a strong supply position. Globally there are three main suppliers of lithium: FMC Lithium (based in Charlotte, NC with lithium holdings in Argentina and Chile), SQM (based in Chile), and Chemetall Foote Corp (a division of Rockwood Holdings based in Kings Mountain, NC). Chemetall supplies 35 percent of lithium demand in the world and has two separate lithium resources, including the only operating U.S. source of lithium raw materials in Silver Peak, Nevada. Most lithium is extracted from brine deposits, but it can also be extracted from ore, which is why Chemetall originally based its operations in Kings Mountain. Chemetall ceased production of lithium carbonate from ore in favor of its lower cost brine resources in the United States and Chile (Davis, 2010).[12]

Concerns have been raised about potential lithium price increases spurred by the growing demand for electric cars. Lithium prices have climbed steadily since the 1970s. In 2007, the cost of lithium carbonate—the main product from which lithium is extracted—increased 49% over the 2006 price, to $3.45 per kilogram (Jaskula, 2007). The prices of other cathode raw materials (manganese, nickel, and cobalt) and metals for foil (copper and aluminum) are also rising along with the rapid growth of emerging economies such as China and India.[13] In addition, cobalt production is heavily dependent on one country, the Democratic Republic of Congo, which produces a third of the world's supply (IndexMundi, 2009). These conditions may raise the future cost of lithium-ion batteries. Appropriate risk governance measures may become important, such as improving capacity to recycle lithium metals and devising trade rules for the stable supply of raw materials.

In addition to the above-mentioned lithium suppliers, a third major U.S. player is Novolyte, a global producer of electrolytes. Two additional U.S.-based firms provide or plan to provide key materials. Batesville, Arkansas-based Future Fuel Chemical appears to be the sole U.S. producer of graphitized precursors for anodes. Honeywell is preparing to become the first U.S. commercial producer of $LiPF_6$ (lithium salt for electrolyte), currently building a manufacturing facility with help from DOE funds.

[12] China is currently producing most of their lithium from ore resources, but that method is not considered cost competitive.

[13] Cobalt prices have increased particularly fast from around $10.6/lb in 2003 to $17.2 /lb in July, 2010. Nickel price increased from $4.37/lb in 2003 to $8.85/lb in July, 2010. Copper has risen from $0.85/lb in 2003 to $3.05/lb in July, 2010. (London Metal Exchange, 2010; U.S. Geological Survey, 2010)

Cell components and electronics. Two U.S. players of global importance in cell components are Celgard, the world's third largest producer of separators, and Novolyte, the only North American producer of electrolytes for lithium-ion batteries, with production facilities in Louisiana and in China. Several industries are involved in cell components and electronics: the inorganic chemical industry (cathode active material), petrochemical industry (anode and carbon electric conductors), organic chemical industry (electrolyte), polymer chemical industry (binder and separator), metal industry (can and foils), and electronics industry. Many current U.S. suppliers are diverse firms for which lithium-ion batteries constitute only a small portion of overall activity.

All cell components (cathode, anode, electrolyte, separator, and other cell components) are designed specifically for lithium-ion battery use. Lithium-ion battery cell producers often develop these core cell components in cooperation with suppliers to fit them into their own battery design. Development of key cell components requires advanced chemical engineering. Other cell components (package, lead, insulator, safety vent, gasket, PTC, and center pin) do not require advanced R&D, but need to meet the battery producer's very specific design requirements. Only a small number of selected companies are able to customize the products. They are often small and located near cell and pack manufacturers.

Electronics are similar to those used for many consumer electronics applications. Battery pack companies often design their own battery management systems[14] and assemble them in-house, using purchased, off-the-shelf electronic components such as chipsets, primarily from Asian semiconductor suppliers. Pack assembly occurs near the customers, meaning all over the world. The cost of chipsets is relatively low, but the cost of manufacturing battery management systems is relatively high. For high-volume production, application-specific integrated circuits (ASICs) and customized chipsets for batteries will be used to bring down the total cost (Deutsche Bank, 2009).

We identified 29 U.S.-based suppliers of cell components and electronics. Many major cell component players are located in Japan and South Korea, where the lithium-ion battery industry for consumer electronics is already well established (Goldman Sachs, 2010). As mentioned earlier, the United States has global players Novolyte (electrolytes) and Celgard (separators). Apart from these, several components are difficult to obtain or are available from only one domestic supplier. For example, Arkema is the sole U.S. producer of anode and cathode binder. Oak-Mitsui is the only producer of copper foil for anodes. Recently, large companies have started to create divisions focusing on lithium-ion batteries to go after the developing market. For instance, 3M and Dow Kokam recently began to produce cathodes, electrolytes and electrolyte

[14] Battery management system controls batteries by checking voltage and cell balancing, and by monitoring the charging status and reporting the data.

additives using their strengths in inorganic and organic chemistry R&D (3M, 2010; Al Bawaba Ltd., 2010).

Integrated systems (cell and pack manufacturers). We found 21 lithium-ion battery cell and pack manufacturers that have U.S. manufacturing locations. However, U.S. pack manufacturers mostly import battery cells from non-U.S. suppliers with only the final pack assembly occurring domestically. Currently, only EnerDel operates its own high-volume anode/cathode coating and cell manufacturing facilities in the United States (Deutsche Bank, 2009).

A123 and EnerDel are relatively new companies with medium-sized production capacities and significant R&D capabilities. A123 has research and engineering locations in the United States, even though A123's cell manufacturing locations are in China and South Korea, partly because of the pre-existing cell component supply chain in Asia. EnerDel has R&D as well as manufacturing capacity in the United States. However, both EnerDel and A123 are still new companies and manufacturing on a scale much smaller than major Asian players, and thus rely heavily on government funding. Having received a $249-million grant from DOE in 2009, A123 plans to build its first U.S. facility to manufacture anode/cathode coating in Romulus, MI, and a cell assembly facility in Livonia, MI (A123Systems, 2010).

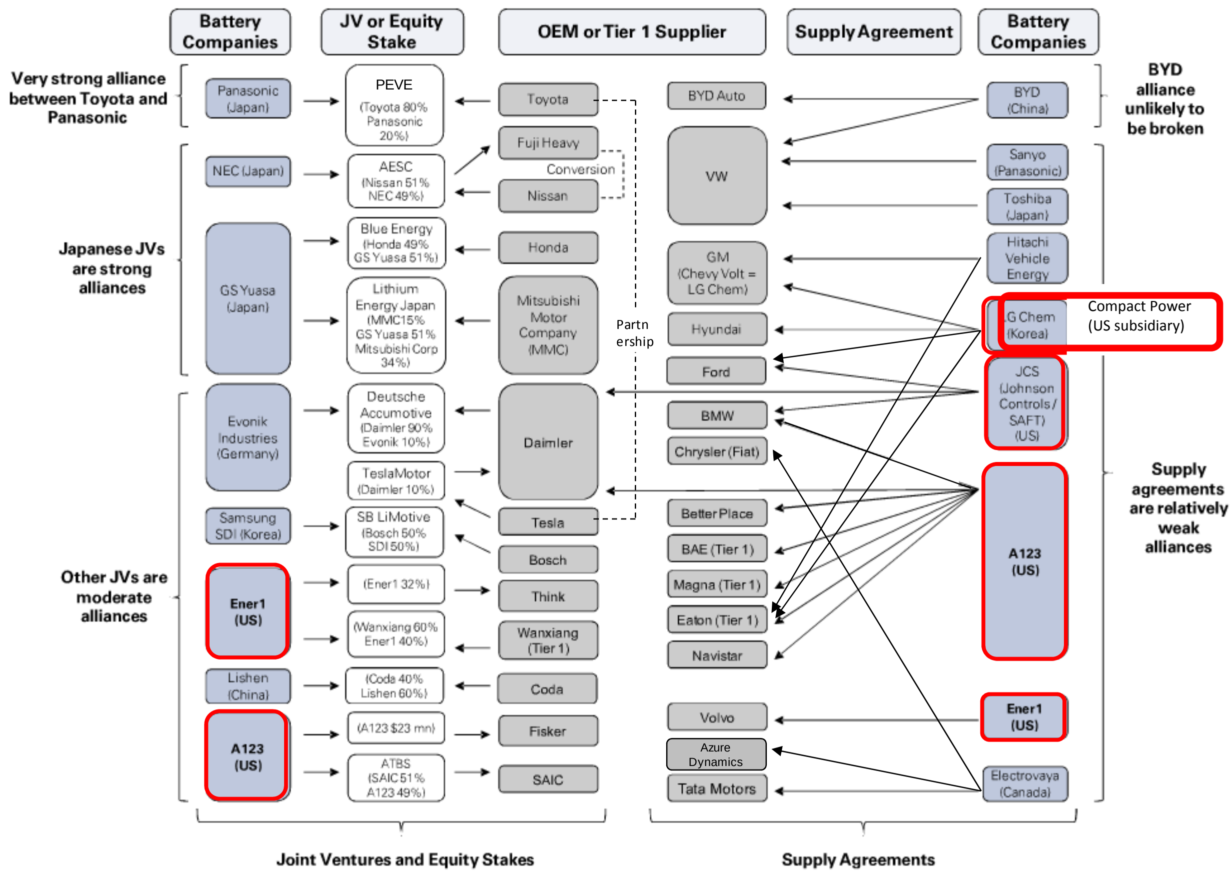
Since U.S. firms are new, they have not yet accumulated the know-how for high-volume production of lithium-ion batteries. Five Japanese and two Korean battery manufacturers are 10 years ahead in high-volume production of lithium-ion batteries (Farley, 2010). Currently, U.S. firms are aggressively catching up to the high speed and precisely controlled processing technologies of the Asian giants. For example, Ener1 is trying to fill holes in its expertise through global mergers and acquisitions. Ener1 purchased Enertech, a major Korean battery maker, as well as the battery division of Delphi (an auto parts supplier) to improve battery processing. Also, Ener1 hired a number of Asian battery engineers to improve their battery R&D (Deutsche Bank, 2009).

Compact Power (subsidiary of LG Chem (Korea)), and JCS (a joint venture of Johnson Controls (U.S.) and Saft (France)) are major non-U.S. players. 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 lithium-ion battery products are held by Saft (Keegan, 2009).

Some battery companies increase their footprint in the supply chain by making key cell components. A123 manufactures battery cells and battery packs and has also become a supplier of iron phosphate cathode materials. LG Chem produces both battery cells and polymer binder for anodes and cathodes in Korea (METI, 2009a).

Vehicles. Battery cell and pack companies and automotive firms often have partnerships or joint ventures (JVs) to develop lithium-ion battery technology for vehicles (see Figure 16). Japanese JVs are especially strong alliances, which is a disadvantage for U.S. battery suppliers because Japan's leading automotive OEMs and experienced battery cell and pack manufactures are collaborating to aggressively develop car battery technology (Goldman Sachs, 2010). Outside Japan, the JVs and the supply agreements are moderate or weak. Non-Japanese automotive OEMs often have multiple battery suppliers and choose them for each vehicle model separately, thus, there is no guarantee of a long-term relationship (Goldman Sachs, 2010). Non-Japanese JVs and the supply agreements are often done between firms located in two different countries. Four major U.S. battery companies—A123, Compact Power (LG Chem), EnerDel, and JCS—each have supply agreements or JVs with U.S. and non-U.S. automotive OEMs.

Figure 16. Alliances and joint ventures between battery firms and automakers



Source: (Goldman Sachs, 2010)

U.S. venture capital startups. We identified 18 startup companies. Following A123 and EnerDel, many venture capital startups are emerging in the U.S. lithium-ion battery market, many of which are based on licensed technology from U.S. national laboratories and universities. Examples include NC State University and Tec-Cel for new types of anode development, NanoeXa and Argonne National Laboratory for cathode and electrolyte additives development, Planar Energy Devices, NREL, and University of Florida for next generation batteries (solid state lithium batteries), and Pellion technologies and MIT for another type of next generation battery (magnesium-ion batteries). These collaborations will accelerate the technology transition from laboratory to mass production.

U.S. venture capital startups have the potential to compete with large Asian battery makers due to their technological competitiveness. For example, A123Systems, started by MIT researchers, emerged in the market in 2001 and quickly signed supplier agreements to provide their cells to major automakers, such as GM and Mercedes. Lithium iron phosphate is a well-known cathode material with several advantages: low cost, rich reserve base, safer material properties, and longer life expectancy (BusinessWeek, 2007; Deutsche Bank, 2009). However, lithium iron phosphate has not been used in batteries due to the notable disadvantages of low energy density and lower temperature performance.[15] A123 solved these problems by using the company's original nano-sized lithium iron phosphate particle technology. This example demonstrates the potential of one key technology to amplify a firm's global competitiveness.

U.S. material recycling. Our research identified only one company, TOXCO, which has attempted to recycle the rare metals in batteries, suggesting that there is significant opportunity for growth in the coming years. In the United States, only California and New York require recycling of lithium-ion batteries (Rechargeable Battery Recycling Corporation, 2009). There are no federal regulations setting targets for lithium-ion battery recycling.[16] The EPA's "Battery Act" (42 U.S.C 14301-14336), which includes $10,000 penalties for violators, only applies to lead acid and nickel cadmium batteries (EPA, 2002). By comparison, California's Rechargeable Battery Recycling Act of 2006 requires retailers to "take back from the consumer a used rechargeable battery (including lithium-ion batteries) of a type or brand that the retailer sells or has previously sold" (California Environmental Protection Agency, 2007). The lack of adequate regulations for lithium-ion battery recycling and disposal enhance the risk of environmental damage created by EV batteries. This risk comes not only from improper disposal of the batteries, but from increased production of battery components.

U.S. R&D and supporting institutions. U.S. national laboratories and several universities are the leading battery R&D institutions in the United States, and they are currently pursuing 59 battery technology development projects (see Figure 17). DOE's U.S. lithium-ion battery road map is very similar to Japan's road map (NEDO, 2009), both of which indicate that the lithium-ion battery technology developed at U.S. national laboratories and universities are among the most advanced in the world. Private U.S. companies do not tend to invest significant amounts in battery technology research as their Asian counterparts do. Thus, U.S. national laboratories and universities play an especially important role in helping U.S. private firms develop advanced battery technologies.

Leading institutions include six national laboratories: LBNL (Lawrence Berkeley National Laboratory), ANL (Argonne National Laboratory), SNL (Sandia National Laboratory), NREL (National Renewable Energy Laboratory), INL (Idaho National Laboratory), and ORNL (Oakridge National Laboratory). These laboratories develop not only next-generation battery technology, but also technologies that private firms need today. For example, SNL researches

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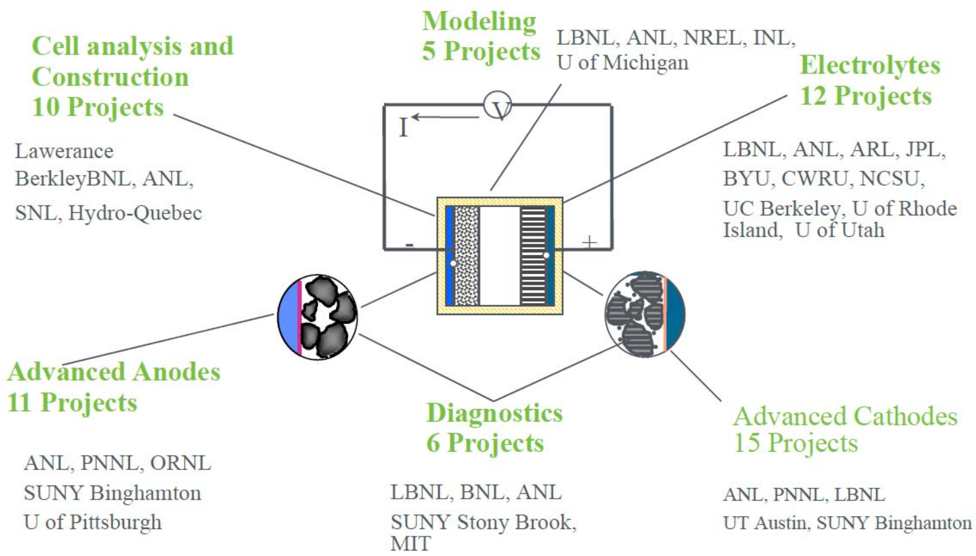
[15] Iron phosphate has a lower energy capacity than other cathode materials (2,010 Wh/dm^3). For example, Cobalt-based oxide has an energy density of 2,880 Wh/dm^3 and Manganese oxide, 1,710 Wh/dm^3 (NEDO, 2009).

[16] In the European Union and Japan, there are regulations requiring lithium-ion battery collection and recycling. In the EU, collection targets are set to 25% by 2012 and 45% by 2016 (WasteOnline, 2005). In Japan, by comparison, regulations call for more than 30% of lithium-ion batteries to be recycled (Battery Association of Japan, 2004).

battery abuse testing systems and NREL is developing battery design and thermal testing systems (Howell, 2010).

Figure 17. U.S. national rechargeable battery projects and players



Source: (Howell, 2010)

Cost breakdown

As mentioned, several key battery components are supplied from overseas, which leads cell makers to choose non-U.S. locations for cell manufacturing. The United States clearly needs more domestic cell component suppliers to capture these high-value activities. Most U.S. pack manufacturers import battery cells and electronic components, and only the final pack assembly and system integration occur in the United States. The cost breakdown is found in Table 7. Because lithium-ion batteries are a research-intensive industry, battery R&D costs are large, representing 14% of total cost (included in “gross profit” in Table B) (Goldman Sachs, 2010). Cells account for 45% of total cost. Cell components also have a high value, 29% of total cost. Only a few U.S.-based firms currently produce cell components, but a number of chemical, polymer chemical, petro chemical, ceramic, and metal companies have potential to provide them in the future.

Table 7. Lithium-ion battery cost breakdown

	Components	$/EV battery	Cost breakdown
Cell Components	Cathode	1,663	10%
	Anode	477	3%
	Electrolyte	447	3%
	Copper foil	184	1%
	Separator	608	4%
	Can header and terminals	1,050	6%
	Other materials	375	2%
	Total material	**4,803**	**29%**
Cells	Labor for cell manufacturing	2,586	16%
	Total cell	**7,390**	**45%**
Electronics	Mechanical components	2,053	12%
	Electrical Components	299	2%
	Electronics (battery mgmt. system)	1,381	8%
	Total Electronics	**3,733**	**22%**
Packs	Labor for pack manufacturing	268	2%
	Total Packs	**11,390**	**69%**
Warranty		228	**1%**
Gross Profit		4,979	**30%**
Total Cost		**16,596**	**100%**

Assumes production of approximately 100,000 25-kWh EV packs per year, using 180-Wh Nickel / Manganese / Cobalt (NMC cells).

Source: CGGC, based on (Deutsche Bank, 2009)

U.S. manufacturing

Largely as a result of financial support by federal and state governments, the U.S. domestic lithium-ion battery supply chain is developing very quickly. In 2009, DOE offered the world's largest funding package related to battery technology development for vehicles. As part of the American Recovery and Reinvestment Act (stimulus bill), DOE offered $2.4 billion of funding to battery-related manufacturers, including auto manufacturers, battery material suppliers, and battery recycling companies (See Table 8). These funds will help establish 30 U.S. manufacturing plants, all playing key roles across the value chain, including materials, components, and production of cells and battery packs. The funding also supports several of the world's first demonstration projects for electric vehicles. An additional $2.6 billion has been provided in ATVM loans to Nissan, Tesla and Fisker to establish electric vehicle manufacturing facilities in Tennessee, California and Delaware, respectively. DOE has also offered $25 billion in low-interest loans to battery companies. To help consumers pay the higher purchase price for electric vehicles, the government offers a $7,500 tax incentive (Deutsche Bank, 2009; DOE, 2010; Komblut & Whoriskey, 2010).

Table 8. ARRA grants to lithium-ion battery manufacturers and material suppliers

Company	Received grants ($ mil)	Parts/components/materials
Johnson Controls	$299.2	Nickel-cobalt-metal battery cells and packs, separators (with partner Entek)
A123 Systems	$249.1	Lithium-ion battery cells, packs and cathode
Dow Kokam	$161.0	Lithium-ion battery cells and packs
Compact Power (LG Chem, Ltd.)	$151.4	Lithium-ion battery cells
EnerDel	$118.5	Lithium-ion battery cells and packs
General Motors	$105.9	Lithium-ion battery packs
Saft America	$95.5	Lithium-ion battery packs, packs
Celgard	$49.2	Separator
Toda America	$35.0	Cathode
Chemetall Foote	$28.4	Lithium compounds
Honeywell International	$27.3	Electrolyte salt
BASF Catalysts	$24.6	Cathode
Novolyte Technologies	$20.6	Electrolyte
FutureFuel Chemical	$12.6	Graphitized precursor for anode
Pyrotek	$11.3	Anode
TOXCO	$9.5	Recycling
H&T Waterbury DBA Bouffard Metal Goods	$5.0	Package

Note: Awardees relevant to advanced battery development other than lithium-ion batteries include Exide Technologies with Axion Power International, East Penn Manufacturing Co., and EnerG2.

Source: (DOE, 2009)

This funding applies not only to domestic firms, but also to non-U.S. firms planning to build manufacturing plants in the United States. As a result, the funding successfully increased private non-U.S. direct investment in U.S. locations. For example, Toda America, a $35-million grant winner and Japanese cathode maker, plans to establish a cathode plant in the United States with capacity to produce 4,000 tons per year (Japan Industrial Location Center, 2010).

In addition to federal government incentives, Michigan state government offered $2 billion in grants and $335 million in tax credits for auto- or battery-makers to locate in Michigan (Keegan, 2009; State of Michigan, 2009). For instance, the Michigan Economic Development Corporation Award convinced South Korea's TSC Company to choose Michigan as the location for its new plant. TSC Company was awarded $3.2 million in the form of tax credits over seven years. The township of Northville also offered TSC property tax breaks (Howard Lovy, 2010).

Firm-level data

We collected data on 50 firms with U.S. manufacturing and R&D locations already in existence or planned to be operating by 2012 (see Table 9). The data yield the following characteristics:

- Almost 50% of companies with U.S. locations are in battery cell and pack production (Tier 1). This distribution of companies with U.S. locations represents a foundation for vertical integration of the lithium-ion battery industry in the United States, but no single company has yet achieved this integration.

- Lithium-ion battery-relevant manufacturing companies range from global U.S. and non-U.S. companies to very small companies with fewer than 10 employees.

- We found only five companies with U.S. locations relevant to key materials (Tier 3). FMC Lithium and Chemetall each produce a lithium compound used in cathode materials. Novolyte produces materials for its electrolytes. Future Fuel Chemical produces graphitized precursors, a key material for anodes. Honeywell plans to begin producing Li-Salt ($LiPF_6$), a key material for electrolytes.

Table 9. Lithium-ion battery-related firms with current and planned U.S. manufacturing, assembly and R&D locations: firm-level data

Company Name (Parent Company)	U.S. Headquarters		Relevant U.S. manufacturing and R&D locations		Total U.S. Employees	Total U.S. Sales (USD mil)	Components involved in U.S. locations
3M	St. Paul	MN	St. Paul	MN	10,000	9,179.0	Cathode active material
A123Systems, Inc.	Watertown*	MA	Ann Arbor*	MI	1,672	91.0	Lithium-ion battery pack; battery cell; cathode active material
			Livonia	MI			
AC Propulsion	San Dimas	CA	San Dimas	CA	N/A	4.5	Lithium-ion battery pack
AllCell Technologies	Chicago	IL	Chicago	IL	8	1.0	Lithium-ion battery pack
Altair Nanotechnologies	Reno*	NV	Anderson	IN	99	4.4	Anode active material
Atmel	San Jose	CA	San Jose	CA	5,600	1,217.3	Electronics (control system)
Applied Materials	Santa Clara	CA	Santa Clara	CA	12,619	5,013.6	Battery cell design
BASF Catalysts, LLC	Iselin	NJ	Elyria	OH	5,000	285.9	Cathode active material
Boston-Power, Inc	Boston	MA	Boston	MA	20	3.9	Lithium-ion battery pack
Celgard, LLC (Polypore)	Charlotte	NC	Charlotte	NC	360	N/A	Separator
Chemetall Foote Corp. (Chemetall)	Kings Mountain	NC	Kings Mountain	NC	200	N/A	Cathode precursors; lithium compounds
			Silver Peak	NV			
Coda	Santa Monica	CA	Santa Monica	CA	4	3.4	Lithium-ion battery pack; battery cell
Compact Power, Inc. (LG-Chem)	Troy	MI	Holland	MI	100	11.2	Lithium-ion battery pack; battery cell
ConocoPhillips[1]	Houston	TX	Houston	TX	30,000	152,840.0	Anode active material
Continental Automotive Systems US Inc. (Continental Teves, Inc.)	Newport News	VA	Newport News	VA	800	358.4	Lithium-ion battery pack
Dow Kokam	Lees Summit	MO	Midland	MI	55	1.0	Lithium-ion battery pack; battery cell; cathode active material
DuPont	Wilmington	DE	Chesterfield County	VA	58,000	26,109.0	Separator
EnerDel Inc. (Ener1 Inc.)	Indianapolis	IN	Indianapolis	IN	487	31.2	Lithium-ion battery pack; battery cell

Company Name (Parent Company)	U.S. Headquarters		Relevant U.S. manufacturing and R&D locations		Total U.S. Employees	Total U.S. Sales (USD mil)	Components involved in U.S. locations
Energetics, Incorporated	Seattle	WA	Seattle	WA	19	3.0	Electric conductor carbon
ENTEK Membranes LLC	Lebanon	OR	Lebanon	OR	29	2.9	Separator
ExxonMobil Chemical	Houston	TX	Irving	TX	1,500	N/A	Separator
FMC Lithium	Charlotte, NC	NC	Charlotte, NC	NC	50	27.5	Cathode precursor; lithium compounds
FutureFuel Chemical Company	Batesville	AR	Batesville	AR	453	106.7	Anode graphitized precursor
General Motors Corporation**	Detroit	MI	Brownstown	MI	100	N/A	Lithium-ion battery pack; relevant automotive OEM
H&T Waterbury DBA Bouffard Metal Goods	Waterbury	CT	Waterbury	CT	20	4.2	Package
Honeywell**	Metropolis	IL	Buffalo	NY	350	350.4	Electrolyte li –salt
Intersil	Milpitas	CA	Milpitas	CA	1,503	611.4	Electronics
Johnson Controls, Inc **	Milwaukee	WI	Holland	MI	1,100	299.2	Lithium-ion battery pack; battery cell
Johnson Controls-Saft	Milwaukee	WI	Holland	MI	N/A	N/A	Lithium-ion battery pack; battery cell
LithChem	Anaheim	CA	Anaheim	CA	8	4.2	Battery cell; electrolyte
Lithium Technology Corp	Plymouth Meeting	PA	Plymouth Meeting	PA	78	7.4	Lithium-ion battery pack
Maxim Integrated Products	Sunnyvale	CA	Sunnyvale	CA	8,765	1,997.6	Electronics
Maxpower Inc*	Harleysville	PA	Harleysville	PA	20	3.4	Battery cell
NGK Insulators Ltd. (NGK Spark Plug Co., Ltd.)	Virginia Beach	VA	Virginia Beach	VA	100	11.6	Insulators
Nissan	Franklin	TN	Smyrna	TN	N/A	N/A	Lithium-ion battery pack
Novolyte Technologies Inc.	Independence*	OH	Zachary	LA	90	N/A	Electrolyte organic solution; electrolyte lithium salt; electrolyte
Oak-Mitsui (Mitsui Kinzoku Co.)	Camden	SC	Camden	SC	54	6.7	Anode Cu foil
Pyrotek Incorporated	Spokane	WA	Sanborn	NY	40	0.9	Anode active material
Quantum Technologies	Irvine	CA	Irvine	CA	101	23.3	Lithium-ion battery pack
Saft America (Saft)	Valdosta	GA	Jacksonville	FL	350	106.1	Lithium-ion battery pack; battery cell

Company Name (Parent Company)	U.S. Headquarters		Relevant U.S. manufacturing and R&D locations		Total U.S. Employees	Total U.S. Sales (USD mil)	Components involved in U.S. locations
SouthWest Nano Technologies	Norman	OK	Norman	OK	17	5.0	Cathode electric conductor carbon
Storage Battery Systems Inc	Menomonee Falls	WI	Addison	IL	35	2.8	Lithium-ion battery pack
			Carol Stream	IL			
Superior Graphite	Chicago	IL	Bedford Park	IL	300	70.0	Anode active material
Tesla Motors	Palo Alto	CA	Palo Alto	CA	646	111.9	Lithium-ion battery pack; relevant automotive OEM
Texas Instruments	Dallas	TX	Dallas	TX	25,000	N/A	Electronics
TIAX LLC	Lexington*	MA	Cupertino	CA	300	N/A	Cathode active material
Toda America Incorporated (Toda Kogyo Co.)	Battle Creek	MI	Goose Creek	SC	57	0.0	Cathode active material
TOXCO Inc.	Anaheim	CA	Lancaster	OH	111	13.5	battery recycling
TSC Michigan (TechnoSemichem)	Northville	MI	Northville	MI	N/A	N/A	Electrolyte
Valence Technology Inc	Austin	TX	Las Vegas	NV	349	16.1	Lithium-ion battery cell and cathode
Yardney Technical Products Inc (Ener-tek)	Pawcatuck	CT	Pawcatuck	CT	160	15.0	Lithium-ion battery pack

[1]Total company employees. *R&D location only. **Employees for this manufacturing location only. Sales data are for 2009 unless otherwise noted. Data are not available for all fields; many private firms do not disclose figures.

Source: CGGC, based on company websites, industry interviews and Selectory database and Hoover's database.

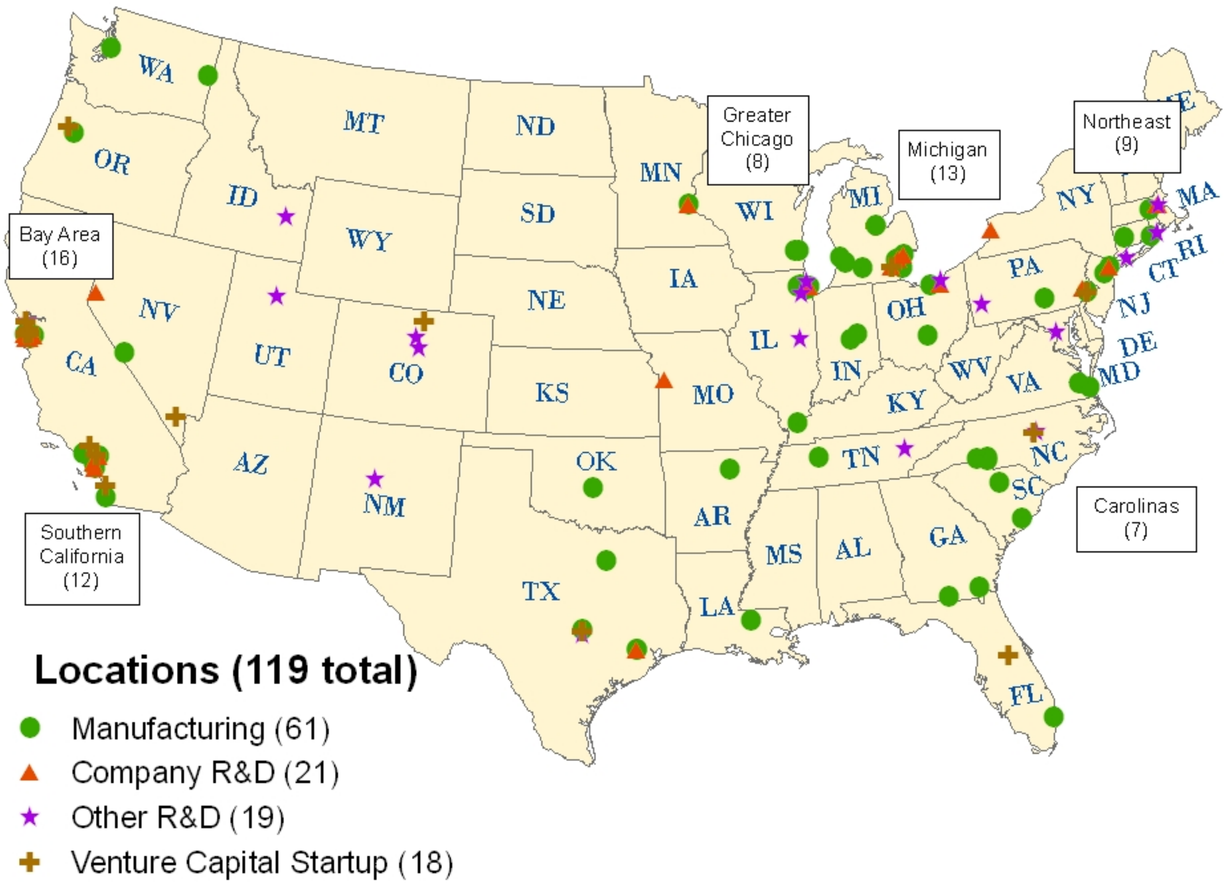
Location-level data

We identified 119 U.S. manufacturing and R&D locations relevant to lithium-ion batteries (see map in Figure 18). These U.S. locations include manufacturing, company R&D, other R&D institutions, and startup firms. The data yield the following characteristics:

- We identified 61 U.S. manufacturing locations distributed over 27 states. The top three states are California, with 28 locations, Michigan (8) and Illinois (6) manufacturing locations.
- We found a total of 40 R&D locations, including 21 representing company R&D, and 19 representing national labs or research centers affiliated with universities.
- Roughly 30% of the total locations are in either California or Michigan, the two states that have U.S. EV automakers—Tesla (California) and General Motors (Michigan).

- For all locations, the map identifies six geographical clusters: the San Francisco Bay Area with 16 locations, southern California (12), greater Chicago (8), Michigan (13), the Northeast Atlantic (9), and the Carolinas (7)

Figure 18. U.S. lithium-ion battery-relevant manufacturing and R&D locations



Source: CGGC, based on industry interviews and company websites.

Startup firms

Our research identified 18 relevant startup firms in the United States (see Table 10). Lithium-ion startup companies have benefited from several sources of federal funding. Some government funds helped to establish entirely new firms. ActaCell received $250,000 in 2009 for its first phase of funding from the Texas Emerging Technology Fund (OneSource Business DB, 2010). Another example is EnerG2, which received a $21-million federal grant to build a plant in Oregon (Engleman, 2009). Several U.S. startup companies have emerged from R&D institutions. In some cases, staff from these institutions are the founders of the startup companies, including

Prieto Battery, which was founded by Amy Prieto, an assistant chemistry professor at Colorado State University (Wilmsen, 2010). In another example, a class project for graduate students in North Carolina State University's MBA program has now become a startup company, Tec-Cel. Tec-Cel aims to commercialize lithium-ion battery applications of a nanofiber technology invented by Professor Xiangwu Zhang, a researcher in the university's College of Textiles (Rzewnicki, 2009).

Data on relevant startup firms yield the following characteristics:

- More than half of the startups are located in California. Eight of the 10 California-based startup companies are manufacturing lithium-ion cells, while only two companies make electrolytes and anode active materials.

- Many of the startup companies were established between 2007 and 2009. This includes Contour Energy Systems (formerly CFX Battery), Envia Systems, Sakti3, Seeo, and Planar Energy Devices. Meanwhile, Quallion started manufacturing of lithium-ion batteries earlier, in 1998, for various applications and started making lithium-ion batteries for HEVs and EVs in 2008.

- These startup companies have a small number of employees, ranging from 3 to 80 employees. Most are highly skilled in engineering or chemistry. Company capital ranges from $50,000 to $32 million.

Table 10. U.S. startup firms in the lithium-ion battery industry

Company Name	U.S. Headquarters		Total U.S. employment	Total U.S. sales	Battery components manufactured	Capital	Year Established
ActaCell	Austin	TX	9	N/A	Battery cell	$5.8	2007
Amprius	Menlo Park	CA	N/A	N/A	Anode active material	$3.0	2008
Atieva	Mountain View	CA	5	1	Lithium-ion battery pack; electronics; soft ware components	$7.0	2007
Contour Energy Systems (formerly CFX Battery)	Azusa	CA	N/A	N/A	Battery cell	$20.0	2007
Dow Kokam	Lees Summit	MO	N/A	N/A	Lithium-ion battery pack; battery cell; cathode active material	N/A	2009
EnerG2, Inc.	Albany	OR	19	2.9	Electrolyte	$32.0	2009
Envia Systems	Hayward	CA	5	1	Battery cell	$12.7	2007
Farasis Energy	Hayward	CA	N/A	N/A	Battery cell	$0.75	2003
Flux Power	Vista	CA	10	2.8	Electronics	N/A	N/A
K2 Energy Solutions	Henderson	NV	18	1.4	Anode active material	$3.2	2006
Leyden Energy	Fremont	CA	5	2.5	Battery cell	$4.5	2007
Planar Energy	Orlando	FL	10	0	Solid state batteries	$4.4	2007
Porous Power Technologies	Plymouth Meeting	PA	N/A	N/A	Separator	$3.5	2008
Prieto Battery	Fort Collins	CO	N/A	N/A	Anode Active material	$0.9	2008
Quallion	Sylmar	CA	80	10	Lithium-ion battery pack; Battery cell	$20.0	1998
Sakti3	Ann Arbor	MI	N/A	N/A	Battery cell	$12.0	2007

Company Name	U.S. Headquarters		Total U.S. employment	Total U.S. sales	Battery components manufactured	Capital	Year Established
Seeo	Berkeley	CA	N/A	N/A	Solid polymer electrolyte	$10.6	2007
Tec-Cel	Cary	NC	N/A	N/A	Anode Active material	$0.05	2009

Source: CGGC, based on company websites and industry interviews.

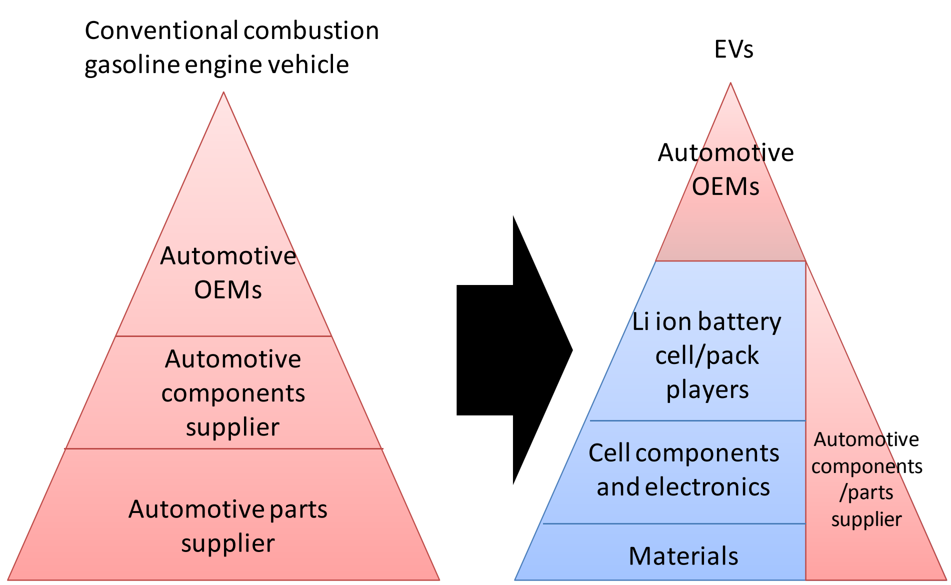
U.S. manufacturing jobs

The U.S. lithium-ion battery industry is still in its infancy. It is difficult to determine the aggregate number of jobs directly related, although it is possible to gain some sense of job creation to date. For example, in 2010, Dow Kokam broke ground in June on a facility in Midland, Michigan that is projected to employ roughly 700 people. In July, Compact Power, Inc., a subsidiary of South Korean firm LG Chem, began building a new facility in Holland, Michigan that is expected to employ 400 people. Also in Holland, a plant being established by a Johnson Controls-Saft joint venture will employ at least 300 (Goodell & Daining, 2010). In September, A123Systems opened the largest lithium-ion automotive battery production facility in North America, expecting to hire more than 3,000 people by 2012 (Chu, 2010).

Some non-U.S. carmakers are also planning to produce batteries in the United States. For instance, in 2010 Nissan broke ground on a large battery plant in Tennessee (Motavalli, 2010). Toyota recently partnered with Tesla (U.S.-based EV-maker) to jointly produce EVs and is aiming to hire 10,000 U.S. employees (Eisenstein, 2010).

In the future, as the automotive industry shifts away from the internal combustion engine toward electric vehicles, the growing importance of advanced batteries will lead to significant labor changes. The entire structure of the auto industry will likely be transformed, as depicted in Figure 19.

Figure 19. Industry structure of conventional combustion vehicles vs. EVs



Source: CGGC based on (Japan Industrial Location Center, 2010)

In a fully electric vehicle, there is no need for an engine, conventional transmission, or many associated components. For the conventional auto industry, the employment implications of this shift will be considerable, involving loss of some traditional jobs and gains in other categories. New jobs related to advanced batteries will include not only the manufacturing and assembly involved in batteries, cells, cell components, electronics, and materials, but also in battery performance testing (Percept Technology Labs, 2010). Industry analysts expect an increase in opportunities in product testing and measurement (EE Times, 2010).

Future of the U.S. supply base

U.S. strengths and opportunities

The United States has the potential to become globally competitive in lithium-ion battery manufacturing for vehicle use due to several important factors:

1) The market is relatively new, so there is still room for new entrants
2) Lithium-ion batteries involve a wide range of chemistries and require significant further improvements to serve in vehicle applications, so U.S. capabilities in R&D and innovation will be key
3) The $2.4 billion in ARRA funding distributed by the DOE has given the United States an important head start
4) The United States will be making the largest share of electric vehicles in the near future, which represents a distinct advantage for battery firms with U.S. manufacturing locations

Focusing on reliability will be crucial during the initial stages of vehicle electrification. A single crash could undermine the industry, so durability, safety, and performance will all be paramount research objectives above simple cost calculations (Deutsche Bank, 2009). A123Systems, Inc. is an example of a U.S. company focusing on a unique battery chemistry. Specifically, A123 is specializing in a proprietary design based on nanotechnology employing lithium-iron phosphate. This design has a relatively low energy density, but compared to alternatives such as manganese spinel, it is cheaper and safer—two critically important properties in the early stages of the lithium-ion battery market (NEDO, 2009). This technological development has the potential to turn into a key product as the United States expands its manufacturing capacity.

Once established, the lithium-ion manufacturing sector will reap economies of scale through manufacturing experience. Component costs may go down 20 to 30 percent in the next few years due to purchasing economies of scale that will lower prices for material suppliers (Deutsche Bank, 2009). Since lithium-ion battery materials are costly to ship from Asia, localized sourcing of materials can be expected as U.S. manufacturing expands and the relevant supply chain scales up.

Moving forward, the United States already enjoys certain competitive advantages, which, if fully harnessed, could capture not just a significant global market share of lithium-ion battery manufacturing, but could end up dominating certain niche markets including medical, aerospace, and especially military (Brodd, 2005).

The U.S. military is the most technologically advanced in the world, conducting two-thirds of the world's military R&D spending. This, along with its past successes as a technology incubator, makes the military sector an obvious niche to pursue. The DOE appears already to be moving in this direction. For example, the one ARRA grant given to Saft America (the leading French battery maker) was intended for military applications (opening a factory in Jacksonville, FL). In fact, most of the lithium-ion battery manufacturing done to date in the United States has been for military applications because the U.S. military has been an early adopter and supporter of domestic lithium battery production (Davis, 2010).

The United States possesses another key advantage stemming from research conducted at its national labs, especially Argonne National Laboratory. Due to partnerships and licensing deals with the private sector, such efforts have helped several important lithium-ion battery technologies make the leap from cutting-edge science to commercialization, including advanced cathode materials developed for Japan's Toda Kogyo and for the world's largest chemical company, BASF (Argonne National Laboratory, 2008, 2009). Similarly, EnerDel (U.S.) is designing proprietary technologies that were first pioneered in Argonne, and startup NanoeXa (U.S.) has cooperated on key licensing deals involving cathodes and electrolyte additive technologies (Chamberlain, 2008; PR Newswire, 2010).

Hybrid buses represent another niche market where the United States excels and has the potential to continue its dominance of lithium-ion batteries for hybrid buses (Lowe et al., 2009).[17] A123 currently has relationships with BAE Systems, Daimler, and Magna, which brought in $35 million in revenue (2009) and allows A123 to command a near 50-percent global market share of lithium-ion batteries for hybrid-electric buses (Deutsche Bank, 2009).

U.S. weaknesses and threats

Japan and South Korea are currently further ahead in lithium-ion battery manufacturing for vehicles, as witnessed by LG Chem (Korea) winning the Ford Focus and GM Volt contracts, and the fact that Nissan and Honda (Japan) are moving quickly to introduce electric vehicles in the United States.

Asia has several vertically integrated companies with 20 years of experience in making lithium-ion batteries. This depth of experience poses a danger that the technological edge currently held by the United States could shift to Asia. Through experience, Asian companies have improved manufacturing processes. It will be vital that the United States focuses on R&D related to manufacturing processes in order to decrease production costs, a necessary step to catch up with Asia.

Similarly, U.S. intellectual property assets may continue to get siphoned off from U.S. companies with manufacturing locations in Asia, especially in China, where intellectual property

[17] For more detail on hybrid heavy trucks and buses, see two previous CGGC reports, *Public Transit Buses: A Green Choice Gets Greener* (2009) and *Hybrid Drivetrains for Medium- and Heavy-Duty Trucks* (2009).

infringement is a real concern. China is an additional threat due to its lower labor and material costs, not to mention offers of zero financing and free facilities, which may continue to lure U.S. companies to Asia.

Certain battery components, such as natural graphite anodes, are considered commodities. They are products that play a key role, but are low-cost and uniform, and relatively easy to make. Applying the spectrum of commoditization to battery components, there are certain important implications for lithium-ion battery manufacturing for vehicle use in the United States. Chief among these is preparing for a possible commoditization of lithium-ion batteries for vehicle use by looking at past experiences.

Since 2005, A123 has supplied the power tool company Black & Decker with 10 million 18650 batteries, which are considered commoditized batteries, similar to laptop batteries. A123's revenue from these orders stood at $30 million in 2008. However, revenue has declined since then, and A123 has exited from their supplier agreement with Black & Decker for 18650 batteries. Because A123 considered profit margins insufficient, it decided to focus on high-end applications and has licensed away its technology to Lishen, a Chinese company (Deutsche Bank, 2009).

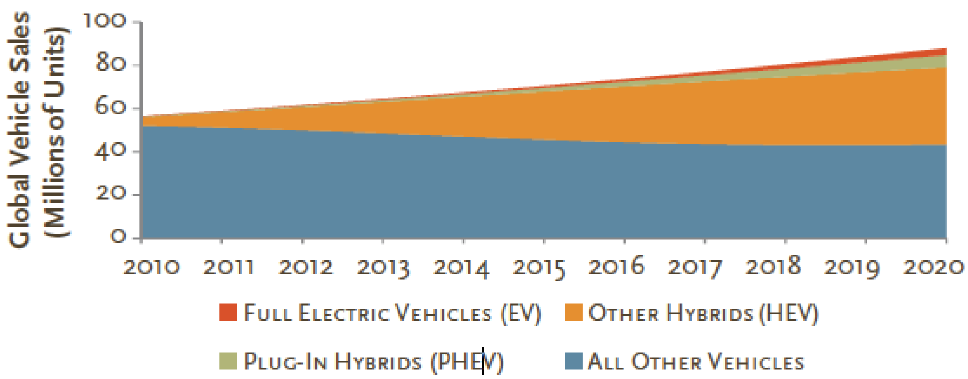
Whether this case holds lessons for lithium-ion battery production remains to be seen. The impetus for avoiding commoditization of lithium-ion batteries is simply to avoid competing with China on labor costs associated with mass production of a commoditized item with low profit margins. Plants in China typically use manually operated facilities for much of their battery production. To counter this, the United States must focus on high levels of automation for its lithium-ion battery plants. To maintain strong profit margins, the United States needs to maintain its high-tech edge on battery R&D and production to avoid competing head-on with China on mass production.

Capacity and demand

As in any new industry, it is extremely difficult to forecast the future market for electric vehicle batteries, and therefore equally difficult to plan future capacity in perfect alignment with demand. Battery firms worldwide face this dilemma; while they feel sure that the market will grow quickly after a certain "take-off" point, they cannot predict with certainty exactly when that take-off will occur, and this makes it difficult to know how to time their plant capacity expansions.

A global forecast by international management consultant firm PRTM—estimating future sales of electric vehicles and all other vehicles—is found in Figure 20. According to this forecast, by 2020, sales of HEVs, PHEVs and EVs will reach approximately 40 million vehicles, representing roughly half of the total market. HEVs will continue to lead the way, making up the bulk of electric vehicle sales while showing a steady shift away from NiMH to lithium-ion batteries.[18] This forecast clearly holds that for the next 10 years at least, the auto market will consist of several different types of vehicles (ICEs, HEVs, PHEVs, EVs) as well as different types of batteries (NiMH, lithium-ion, lead-acid). Other industry sources agree that all will likely coexist in different stages and locations, so there may be no single clear winner (Wise, 2010).

Figure 20. Global vehicle forecast, 2010-2020



Source: (PRTM, 2010)

Some market forecasts are more modest. According to Total Battery Consulting (TBC), for instance, the EV and PHEV market will be 200,000 vehicles in 2015 and one million by 2020, substantially lower than the PRTM estimates. TBC concludes, even from its more modest forecast, that the plant openings and expansions supported by ARRA funding will lead to overcapacity starting in 2013 (Farley, 2010). Similarly, strategy consultant firm Roland Berger predicts that by early 2015, global capacity for lithium-ion batteries will be double the amount needed to satisfy projected 2016 demand (Roland Berger Strategy Consultants, 2010).

U.S. production capacity has indeed grown very quickly, from just two relevant plants before the ARRA funding, to 30 planned sites aiming to achieve a projected 20% of world capacity by 2012, and 40% by 2015 (DOE, 2010). With such rapid growth in a new market, the possibility of a capacity-demand mismatch cannot be ignored. Industry analysts have warned that among the several companies gearing up to enter the market, some will fail or be bought out. One estimate maintains that only 6-8 Tier 1 battery manufacturers will be able to survive the global market in the coming 5-7 years with the minimum of 600 million Euros in revenue necessary to survive by 2015 (Roland Berger Strategy Consultants, 2010).

[18] Analysts anticipate that lithium-ion batteries in HEVs will increase steeply, from a 35% penetration rate in 2015 to a 50% penetration rate in 2017 (Deutsche Bank, 2009).

Still, even forecasts of overcapacity acknowledge that, within a very short period, the industry will no longer be facing excess capacity, but instead, excess demand. One such scenario by analysts at Deutsche Bank emphasizes a capacity utilization of only 52% in 2015, but 145% in 2015—meaning that just two years after the "overcapacity" scenario, demand will exceed capacity by 45%. This reflects the HEV shift away from NiMH batteries to lithium-ion batteries, which are expected to move from 35% to 50% penetration in those two years. Such numbers underline the dilemma the industry faces, in a fast-changing market in which forecasts can vary widely and become quickly outdated.

Table 11. Outlook for lithium-ion battery demand, capacity, and use, EV-equivalent in thousands of units

2015 scenario for US, Europe, and Japan						
	Demand subtotal	LIB Penetration	LIB-Only	EV-Equivalent	% by EV-Equivalent	NMH Demand
Mild Hybrid	1,343	35%	470	24	3%	873
Full Hybrid	1,674	35%	586	59	7%	1,088
PHEV	736	100%	736	368	47%	-
EV	332	100%	332	332	42%	-
Total	**4,085**		**2,124**	**782**		**1,961**
	Capacity utilization - on 2015 capacity est			52%		

2017 scenario for US, Europe, and Japan						
	Demand subtotal	LIB Penetration	LIB-Only	EV-Equivalent	% by EV-Equivalent	NMH Demand
Mild Hybrid	2,363	50%	1,181	59	3%	1,181
Full Hybrid	1,913	50%	957	96	4%	957
PHEV	2,061	100%	2,061	1,030	47%	-
EV	1,006	100%	1,006	1,006	46%	-
Total	**7,343**		**5,205**	**2,191**		**2,138**
	Capacity utilization - on 2015 capacity est			145%		

Source: (Deutsche Bank, 2009)

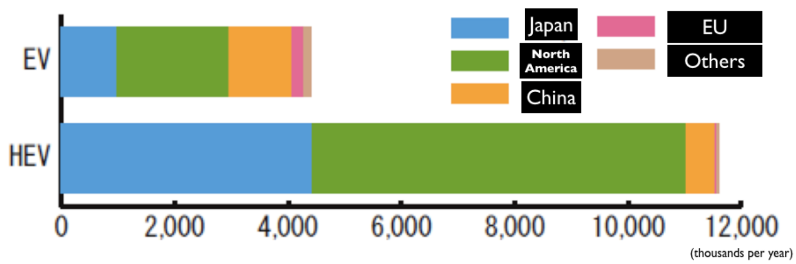
Forecasts may also be underestimating the potential popularity of electric vehicles, similar to how industry experts underestimated how popular the Toyota Prius (HEV) would become. In 2001, only 29,000 Priuses were sold worldwide, but by 2007, Toyota sold 290,000 (181,000 in the United States). Many names were added to waiting lists, but Toyota was forced to forego sales that would have been much higher if the firm had been prepared for the unexpectedly high level of demand (Welch, 2009).

In addition, some capacity/demand forecasts are based on past estimates of battery costs, and these costs are coming down much more quickly than anticipated. LG Chem Chief Executive Bahnsuk Kim recently remarked that he expects a 50% drop in battery prices by 2015, which he believes will be sufficient to drive higher demand (Woodall, 2010). The DOE projects that the cost of some batteries for electric vehicles will decrease by nearly 70% before the end of 2015 (DOE, 2010).

Since industry analysts are in general agreement that demand for electric vehicle batteries will be very strong in the medium and long term, and perhaps as early as 2017, U.S. firms are watching the market carefully to make decisions about capacity. According to one interview, the U.S. automotive industry is in "wait-and-see mode…waiting to see how well the Volt and the Leaf do and if or how quickly the market develops" (Davis, 2010). Some non-U.S. firms appear to be forming proactive strategies to take these market uncertainties into account. For instance, Japanese companies appear to be introducing electric vehicles in the United States in a loss-leader strategy—pricing the product less than profitably in order to build future market share (Wise, 2010).

An important factor is the distinct edge the United States has at the end of the value chain, in the manufacture of electric vehicles that will use lithium-ion batteries (Nishino, 2010). The North American auto industry is well positioned to lead in the ability to manufacture electric vehicles, with far greater production capacity than Japan, China, EU or others (see Figure 21). This is especially important to battery firms, since batteries will likely need to be produced close to the end-use market, which in this case appears to be the United States, and more specifically, close to Michigan due to its pre-existing auto-manufacturing sector.

Figure 21. Forecast of production capacity for cars using lithium-ion batteries, 2015



Source: (Nishino, 2010)

In sum, a careful analysis of capacity and demand issues suggests that for U.S. firms, the risk of expanding capacity ahead of the market may actually pale in comparison to the opposite risk: that of not being prepared to lead this new industry, and thus potentially losing the U.S. edge in the global automotive sector. Our interviews suggest that the United States must adopt a long-term perspective on lithium-ion battery manufacturing. Indeed, it would be myopic to assume that the ultimate goal is merely a U.S. supply chain for batteries, when instead it should be a total reinvention of the U.S. automobile sector to embrace producing electric vehicles (Wise, 2010).

Future strategies

The Obama administration released a plan in July 2010 with ambitious targets across the electric vehicle spectrum, demonstrating that the United States is placing a high priority on retooling the automotive manufacturing sector for electric vehicles. Listed here are some of the Administration's goals (DOE, 2010):

- Put one million PHEVs on the road by 2015.

- Increase U.S. plants' capacity in order to produce batteries and components for up to 500,000 electric-drive vehicles per year by 2015.
- Support the world's largest electric vehicle demonstration to date, with 13,000 grid-connected vehicles and 20,000 charging stations nationwide by December 2013.

As the United States moves forward, it faces Asian competitors with 20 years of experience making lithium-ion batteries for consumer electronics (Davis, 2010). To achieve volume production of lithium-ion batteries for vehicles, U.S. firms will need to employ the right set of strategic measures to become globally competitive in advanced lithium-ion battery manufacturing. To overcome the threats of Asian incumbency and potential mismatch of capacity and demand, the United States will need to make the most of its research and innovation strengths, its lead firms such as Celgard, Novolyte, Chemetall, and A123Systems, and the head start provided through Recovery Act funding.

Previous experience highlights the effectiveness of a concerted, strategic push to develop a future value chain. During the 1980s, when Japan controlled the microchip industry, the U.S. government and 14 domestic semiconductor manufacturers formed "Sematech," a strategic partnership a public-private partnership run by U.S. corporations. The goal was to accelerate U.S. basic research in semiconductors. Within five years, the United States was once more the leader of semiconductor innovation including such companies as Intel, AMD, Micron, and IBM. Although the semiconductor industry is now largely concentrated in China, the United States still boasts many of the highest-value companies, including Apple and Intel (Chamberlain, 2008). Today, DOE, through its Vehicle Technologies program and ARRA funding, has undertaken a similar partnership between leading battery manufacturers and research institutions, to put the United States in the leading position. This type of strategic measure falls into the category known as "domination strategies."

Below is a Threats-Opportunities-Weaknesses-Strengths (TOWS) matrix, which builds on a traditional SWOT analysis to determine appropriate future strategies for the U.S. lithium-ion battery value chain (see Table 12). The four types of strategies highlight the importance of the options the United States faces, and present different strategies for capturing and maintaining market share in a still-forming industry. The matrix offers specific strategies for harnessing the strengths and opportunities, while also dealing effectively with weaknesses and threats.

Table 12. Strategy matrix of strengths, weaknesses, opportunities, and threats - U.S. lithium-ion battery supply chain

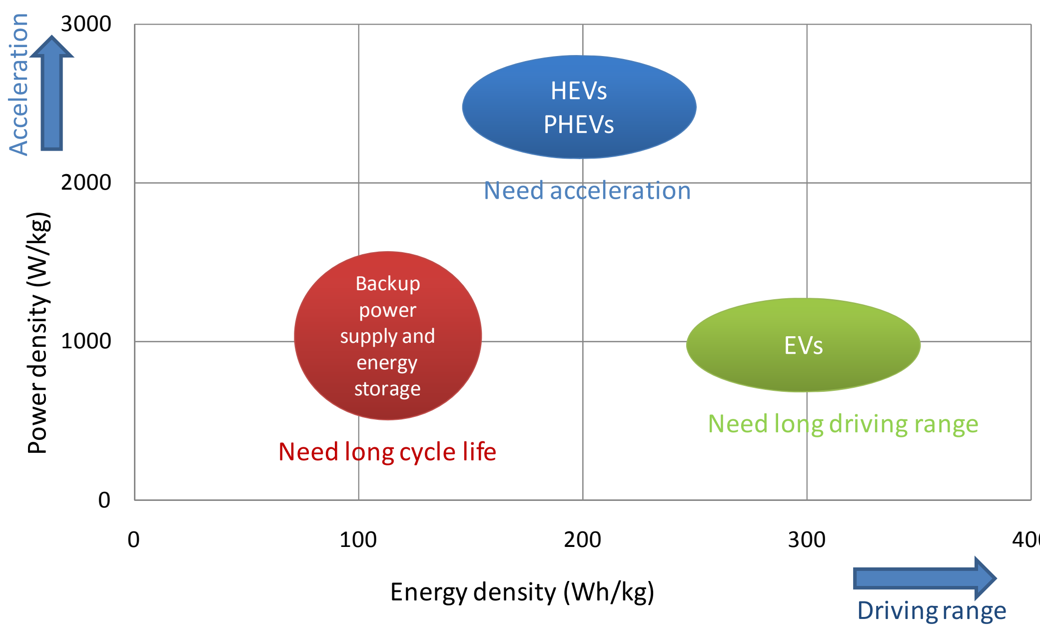
Sources: CGGC based on (Dunn, 2010; Nishino, 2010; PR Newswire, 2010)	**Opportunities** 1. The United States will have the highest demand for electric vehicles by 2017, favoring lithium-ion battery manufacturing nearby, since vehicle manufacturers prefer to source batteries locally 2. The United States can become main supplier to very large niche markets in military, aerospace, medical 3. Recession can be used to revitalize and shift automotive sector into electric vehicles and concomitant technologies	**Threats** 1. Chinese labor and material costs are lower 2. Zero-financing by Asian governments may lure U.S. companies away 3. Predicted capacity mismatch in 2013-2017, especially in the United States and Japan, may eliminate all but a handful of Tier 1 battery firms 4. Technological edge may shift to Asia through manufacturing experience 5. Intellectual property assets may get lost if U.S. companies locate in China 6. Asian companies are moving aggressively ahead to capture market share by expanding manufacturing capacity in the United States
Strengths 1. Several R&D centers including Argonne National Laboratory 2. Technological and innovative edge evidenced by wealth of patents and research papers 3. The United States is developing unique lithium-ion chemistries which may be more important in the early stages due to safety concerns 4. A123Systems is dominant in the hybrid electric bus market 5. Existing automotive manufacturing base in “rust belt” has highly-trained workforce with automotive skills, automotive clients, reasonable labor rates, and attractive real estate market including unused facilities	**SO/Domination strategies** • Retool Midwest for battery production with state and local incentives e.g., as Indiana did with EnerDel ($69.9 million) • Support companies producing unique chemistries to capture distinct market segments and build brands of reliability, durability, and safety • Foster relationships between government, research institutions and industry to enable commercialization of technologies • Build batteries with 10-year lifespan and beat competitors on durability, which will be key in nascent industry that cannot afford thermal runaway incidents • Support U.S. dominance of batteries for hybrid electric buses • Build relationships with military, aerospace, and medical sectors	**ST/Bring-it-on strategies** • Outflank Asian companies by offering financial incentives as well as facilities • Emphasize success of DOE funding to leverage successive rounds of public and private funding, which will attract companies and scientists worldwide • Support firms taking loss-leader positions to remain after the coming market consolidation; since only a handful of firms are expected to prevail in a coming exclusive market, it will be much harder for market entrants in 2013-2017 than today • Support research labs with government funding and private partnerships to maintain technological edge, maintain intellectual property, increase lucrative patent filings • Focus on automation of lithium-ion battery manufacturing to avoid competing with China on labor costs
Weaknesses 1. The United States has few vertically integrated battery companies 2. There is a smaller market for batteries in the United States in the short-term compared to Asia 3. U.S. companies have 20 years less experience in field compared to Asian companies’ head start	**WO/Mitigation strategies** • Use increasing demand to support vertical integration of U.S. companies • Focus on niche markets including military, aerospace, and medical • Incentivize U.S. battery companies with Asian locations to return, along with manufacturing expertise	**WT/Minimization strategies** • Utilize nimbleness of smaller companies in smaller market and focus on niche areas • Put “all eggs in one basket” by concentrating support to 1-2 major U.S. companies to compete head-on with aggressive and integrated companies in Asia

Synergies with other clean energy technologies

As the energy storage capacity of lithium-ion batteries improves and costs come down, these batteries will become increasingly attractive for energy storage beyond vehicles. Indeed, some analysts estimate that electric grid applications could eventually create a larger market than vehicles (Engardio, 2009). Non-vehicle uses will likely include backup power supply,[19] military, and satellites. Most such applications currently use lead acid or nickel metal hydride (Ni-MH), but are expected to move to lithium-ion batteries. Focusing on profitable and sustainable technologies, this section will discuss diverse energy storage markets, including industrial and residential energy storage systems as well as wind energy stabilization.

Energy storage applications require different battery performance compared to EV use. Energy storage demands higher durability of cycle life and requires less power and energy density (see Figure 22). Therefore, energy storage might use different battery chemistries and designs.

Figure 22. Lithium-ion battery power density and energy density required by 2020, by application



Source: CGGC based on (Electro to Auto Forum, 2009; NEDO, 2010)

[19] Backup power supply applications primarily consist of UPS (uninterruptible power supply) and radio wireless station backup power supply. UPS has an electric generator and rechargeable batteries, which supply electricity to computers when electricity input accidentally stops.

Energy storage to increase penetration of solar and wind power

Lithium-ion batteries have potential to increase the reliability of solar and wind power generation. First, energy stored in the batteries can be used to stabilize intermittent energy outputs generated from solar and wind power. Second, they can be used to store excess energy during periods of high production, for instance during the day for solar power (Lombardi, 2009). With further development of lithium-ion batteries, solar and wind power could become more reliable during energy production periods, and available during non-production periods through the use of battery-stored energy.

Decreasing usage costs will boost the application of lithium-ion batteries to industrial and residential energy storage applications, making it possible to avoid using expensive peak-time electricity. Instead, consumers can use electricity stored during less expensive off-peak hours.

Peak-time electricity is not only expensive, it also has higher emissions. Utilities have a loading order, so that they run their lowest-cost plants first to meet “baseload” demand, then use increasingly expensive plants to meet higher demand as needed. The lowest-cost plants are newer, more efficient, and have better pollution controls. During peak demand, utilities often must run their least efficient, most polluting options, typically older natural gas, oil, and coal-fired plants. During off-peak hours, utilities ramp back and shut down their more expensive plants. Lithium-ion batteries used for energy storage could help reduce peak time emissions by storing “cleaner” electricity for use during peak hours instead of the less efficient and dirtier “peaker” plants.

Decentralized and centralized energy storage

A similar synergy can be harnessed for an application called “vehicle-to-grid” (V2G). EV batteries can charge during off-peak hours and sell the energy back to utility companies during peak hours, such as when vehicles are parked all day at work places. The federal government as well as utility companies see V2G as a market driver for PHEVs. In July 2010, the DOE established a goal of establishing 40 million smart meters and one million PHEVs by 2015 (Environmental Leader, 2010). Several utility companies have started testing V2G, partnering with local governments. PG&E, a California utility, has demonstrated V2G with the Bay Area Air Quality Management District (PG&E, 2007). Xcel Energy has begun commercial testing of V2G using 60 PHEVs with the city of Boulder and Boulder County in Colorado[20] (Xcel Energy, 2008). Google is also testing V2G to get into the smart grid/changing service business (Addison, 2009). According to Zpryme Research & Consulting, V2G market size will be $26 billion by 2020 (Environmental Leader, 2010).

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[20] Xcel Energy’s project uses NaS batteries for energy storage.

In September 2010, Federal Energy Regulatory Commission (FERC) Chairman Jon Wellinghoff said that electric vehicle drivers should be able to make money in V2G arrangements, which would help reduce the costs of vehicle ownership while helping utilities continuously balance energy supply and demand on the grid. Wellinghoff noted that this could earn vehicle owners up to $3,000 per year (LaMonica, 2010). The needed technical capability already exists, but utility regulations would have to change, and new types of businesses would need to emerge. An example in progress is a pilot program at the University of Delaware that started in 2007 with five converted Toyota Scions. In January 2010, the university licensed its V2G system for the first time to an outside party, Delaware-based AutoPort. AutoPort will partner with the university and with AC Propulsion to retrofit 100 vehicles. Each V2G vehicle is projected to be capable of discharging 19 kilowatts of electrical power, enough to power 12 homes (Katers, 2010).

If the cycle durability of lithium-ion batteries improves significantly, it might also be possible to reuse vehicle batteries as home energy storage devices. In a vehicle the battery pack will degrade at a rate of about 1% per year, so that after 10 years, a 5-kW battery will perform closer to 4.5 kW, no longer sufficient for vehicle use. Such batteries may find a second use as a home energy storage device or emergency power supply (Dell, 2010). However, since battery size and weight are not crucial factors in home energy storage, battery types other than lithium-ion batteries, such as NaS or zinc-bromide batteries, might be better suited to this use. NaS and zinc-bromide batteries offer superior cycle life and lower cost, and their greater size and weight are acceptable for non-mobile energy storage (METI, 2010; Rahim, 2010).

Grid energy storage is a rapidly developing area for battery firms. A123Systems is a domestic leader of lithium-ion battery applications for utilities and is growing its grid storage business. A123's sales for grid storage went from zero in 2007, to 15% of company sales in 2009. The company's rapid expansion in the grid energy storage market is due to the higher profitability compared to consumer applications, such as electric tools. Partnering with AES Energy Storage, A123 installed a 2MW system in California and a 16MW in Chile's Atacama Desert, both at AES facilities. Also, Southern California Edison, a utility giant, recently ordered two pilot facilities (Garthwaite, 2010). A123Systems' commercial success in lithium-ion battery applications for utilities may induce other U.S. battery companies to enter the utility market.

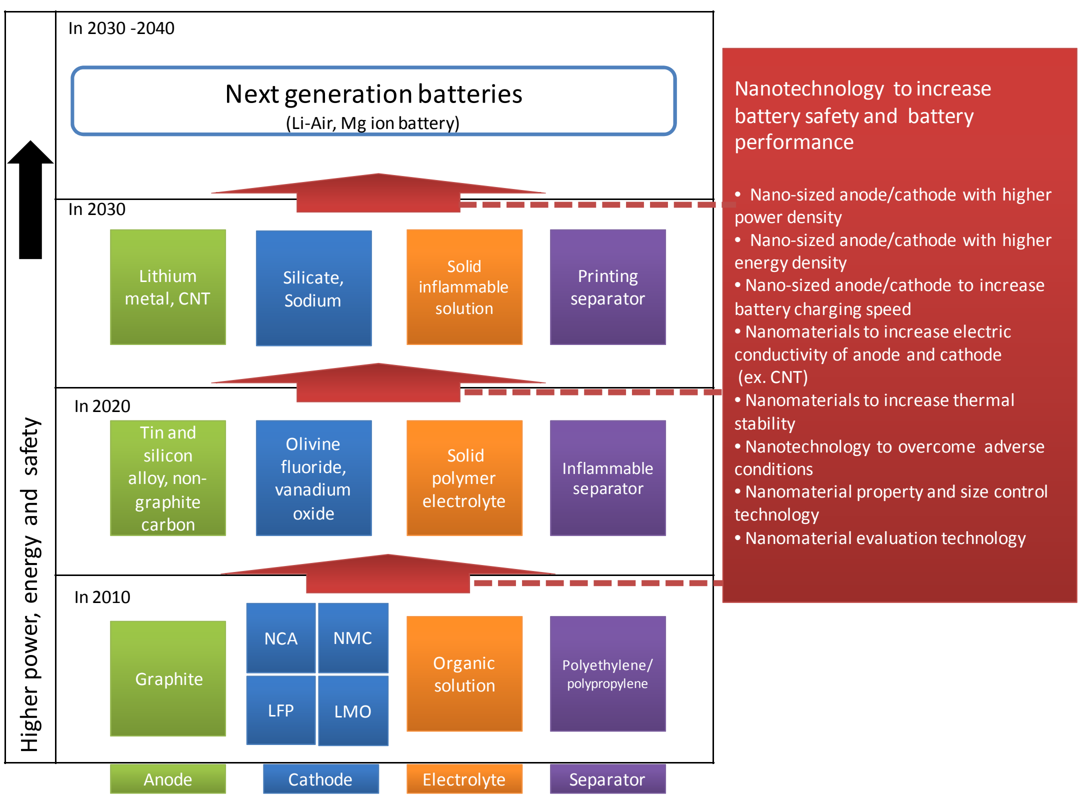
Currently, this utility business is supported by federal and state loans and grants. A123 received a $5-million loan from Massachusetts, which will create 250 jobs. The company also received a $2-million grant from Michigan for grid storage technology development in Livonia, MI. (Garthwaite, 2010). AES similarly received a $17.1 million loan guarantee from DOE to establish a 20-MW grid storage system, which will use A123 lithium-ion batteries and will be built in Johnson City, NY. These grid storage systems will allow consumers to tap into more sustainable sources of power such as wind and solar (Fehrenbacher, 2010).

Nanotechnology

Several potential material developments to increase the performance of future batteries will be accomplished with the use of nanotechnology—creating nano-sized (10^{-9} meters) materials through atomic scale manipulations. Nanomaterials demonstrate different chemical and physical properties from micro-sized materials (10^{-6} meters) because of their significantly smaller particle size. The unique properties of nanomaterials offer significant potential to improve battery performance.[21]

Nanotechnology is expected to improve the performance of three parts of a lithium-ion battery: cathodes, anodes, and separators. Figure 23 shows a road map for battery technology for vehicle use, including the development of lithium-ion batteries from 2010 to 2030 and next-generation batteries emerging after 2030. These new types of battery materials will increase the performance of future batteries through higher energy density, power, and safety.

Figure 23. Lithium-ion battery road map and nanotechnology



Source: CGGC based on (DOE, 2009; NEDO, 2008)

[21] Not all nano-sized materials have unique properties. Many "nanotechnology" applications are reported, but some merely use nano-sized materials whose properties are the same as micro-sized materials, and do not yield unique nano-particle properties.

The following are examples of nanotechnology applications for lithium-ion battery development:

Anode: Carbon nanotube (CNT), one of the most anticipated next-generation anode materials, improves the power performance of lithium-ion batteries by a factor of 10 (Johnson, 2010). CNT will be used as both an anode/cathode electric conductor and also anode active material.

Anode : Altairnano's nano-sized new type anode, lithium titanate oxide, can be charged very quickly, so that a 35-kWh battery pack can be charged in 10 minutes (Blanco, 2007).

Separator: A new type of nano-sized ceramic separator enhances battery safety because of its robustness and stability in high temperatures (Deutscher Zukunftspreis, 2007).

Some nanomaterials can be constructed through a "bottom-up" approach, which entails tailoring nanomaterials at the atomic level instead of the less precise method of breaking down larger bulk materials. This opens up the potential for many innovative approaches to lithium-ion battery development. For example, a team at the Georgia Institute of Technology developed new silicon and carbon nano-composite anode materials that demonstrated five times the energy capacity compared to a conventional graphite anode (Cellular News, 2010). Rice University developed a "coaxial cable" cathode material, which is cobalt oxide cathode material (NCA) stored inside of CNT. The compound of CNT and NCA improves battery performance significantly (Shaijumon, 2009). Many other lithium-ion battery performance improvements are continuously being reported from across U.S. universities and research institutions. These significant advances in nanomaterials will accelerate lithium-ion battery development.

U.S. chemical giants such as DuPont, 3M, and Dow Chemical, as well as many startups, have entered the lithium-ion battery material market using nanotechnology expertise. For example, DuPont recently entered the separator market, developing nanofiber separators, which it claims can increase battery power 15-30% and increase battery life by 20%. DuPont plans to expand production capacity at its plant in Chesterfield County, Virginia, for high-volume production, in addition to their current small-capacity facilities in Wilmington, DE, and in Seoul, South Korea. The Chesterfield County plant is projected to supply separators for 200,000 EVs (Calgary Herald, 2010).

Fuel cells, advanced electronics, and biotechnology

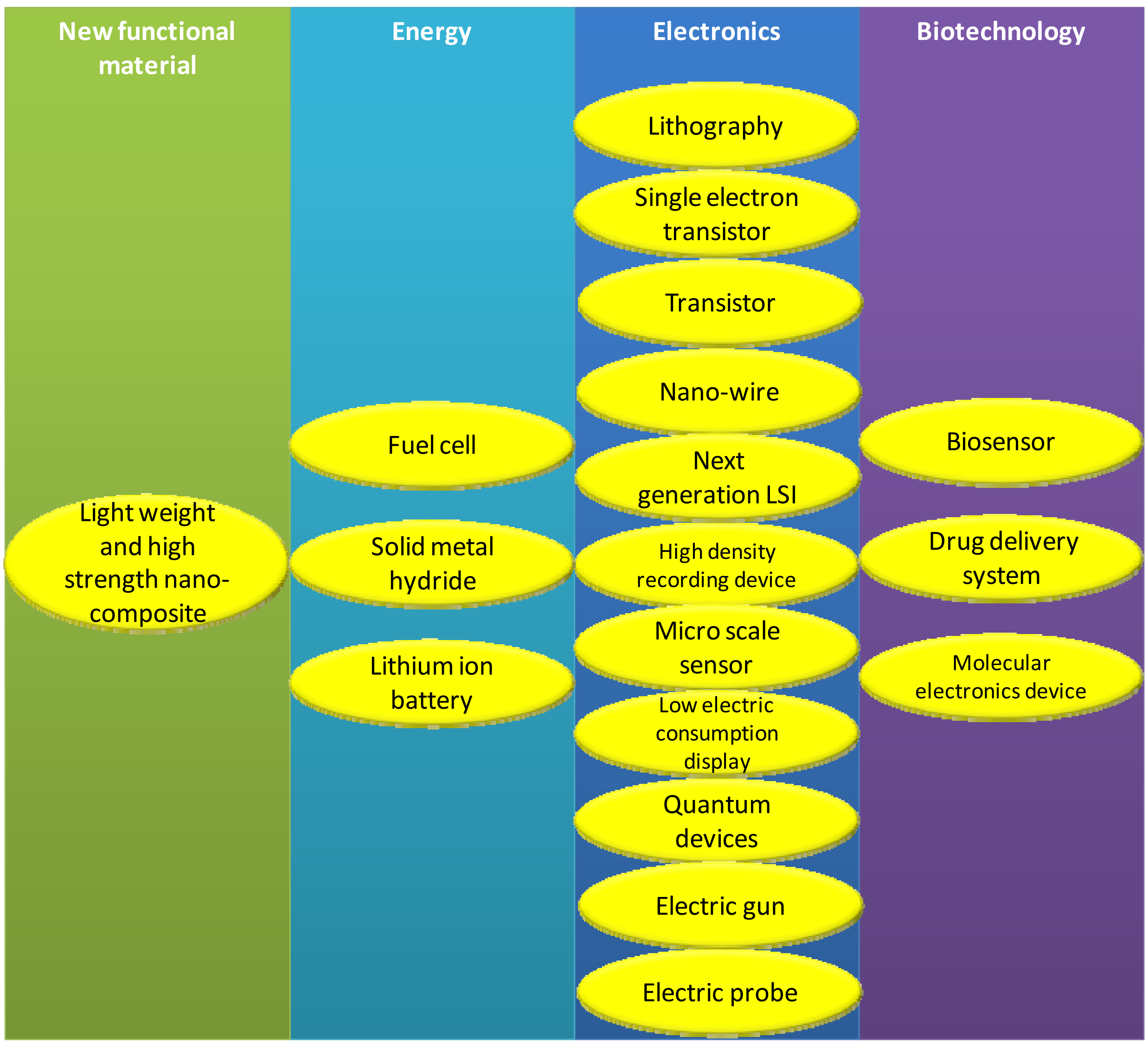
CNT, one of the most promising nanomaterials for future lithium-ion batteries, has much potential to be used for other applications, such as new functional materials, energy, electronics, and biotechnology (see Figure 24).

New functional material: Sporting goods (e.g., tennis rackets and golf clubs) will use CNT due to its lightness and strength. High electric conductivity paints and plastic materials will also make use of CNT's high electric conductivity.

Energy: CNT is expected to be used in fuel cells. CNT can act as a fuel cell catalyst and hydrogen storage material (solid metal hydrate).

Electronics and biotechnology: With CNT's high electric conductivity and its small size, many kinds of micro scale devices will become available.

Figure 24. Carbon nanotube technology: possible applications



Source: CGGC based on (METI, 2007)

Table 13. Major U.S. players in CNT manufacturing and R&D

	Research & development	Manufacturing
Firms	Battele, DuPont, Hyperion Catalyst, IBM, Intel, GE, Motorola, Lockheed Martin	Bucky, Catalytic Materials, CNI, Hyperion Catalyst, MER, Nanocs International, Nanotechnologies Carbolex, Nanotechnologies Carbon Solutions, SES Research, Southwest Nanotechnologies
Universities	Georgia Institute of Technology, MIT, Rice Univ., Univ. of CA, Univ. of KY, Univ. of OK	
Research institutions	Argonne National Lab, Lawrence Berkeley Lab, NASA, Oak Ridge National Lab, Sandia National Lab	

Source: CGGC based on (METI, 2007)

To maintain U.S. global competitive and market advantages, research institutions and private firms could cooperate to move CNT technologies to high-volume production. Currently, high-volume CNT materials are only used as carbon electric conductors in lithium-ion battery anodes and cathodes (METI, 2007). In the United States, CNT has been researched aggressively, and many techniques have been developed, such as CNT atomic manipulation and size-controlling technologies. Major consumer electronics companies are researching CNT, along with smaller players that have already started producing small samples (See Table 13). Hyperion Catalyst was the first to begin mass-producing CNT (METI, 2007).

Conclusion

The automotive industry is moving away from internal combustion engines toward electric drivetrains, and advanced batteries are the key to this shift. The United States will need to be capable of making lithium-ion batteries in order to remain competitive. Most projections agree that a rapidly increasing share of new vehicle sales will consist of hybrid-electric, plug-in hybrid, and all-electric models. This means that what's at stake for the United States is not just its role in lithium-ion batteries, but also its future position in the auto industry.

With the help of stimulus funding and strategic state-level support—especially from the state of Michigan—the U.S. value chain for lithium-ion batteries for vehicles is developing quickly. At least 50 firms are performing manufacturing and R&D in an estimated 119 locations spanning 27 states. To date, much of this activity has focused on battery pack assembly and key materials. In order to become more vertically integrated, capture more value, and compete for contracts from automakers, U.S.-based firms will also need to increase their capabilities in producing cells and cell components—the focus of several of the 18 startup firms now entering the industry.

The United States has several strengths on which to build a lithium-ion battery industry, one of which is the industry's projection that, in the near future, the largest share of electric vehicles will be made in the United States. Other U.S. advantages include outstanding R&D capabilities at national labs and universities and a jump start provided by federal and state funding. Domestic firms can play to these strengths by capturing distinct market segments and building brands of reliability, durability, and safety. It will be important to foster relationships between government, research institutions and industry to successfully bring technology advances to market.

U.S. firms and their competitors all face certain challenges, such as cost issues and a projected lag time between soon-to-be established production capacity and the electric-vehicle demand needed to fill it. More work is necessary to accelerate the U.S. demand curve. To build on its momentum and compete with well-established Asian firms that engage in mass production, the United States will need to emphasize advanced technologies for automated production.

The lithium-ion battery industry has additional significance well beyond its value chain. Thanks to these batteries, electric vehicles will eventually have the ability not only to draw power from the grid but also to sell it back in non-peak times, an important step in the evolution of decentralized energy and the smart grid. In addition, lithium-ion battery developments offer synergies with other clean energy technologies, potentially enhancing the reliability of solar and wind power. Future battery advances also will likely contribute to improvements in fuel cells, advanced electronics, and biotechnology.

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