The Lithium-Ion Battery Industry For Electric Vehicles

by

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Bachelor of Engineering in Mechanical Engineering
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Submitted to the Department of Mechanical Engineering
In Partial Fulfillment of the Requirements for the Degree of
Master of Science in Mechanical Engineering

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Abstract:

Electric vehicles have reemerged as a viable alternative means of transportation, driven by energy security concerns, pressures to mitigate climate change, and soaring energy demand. The battery component will play a key role in the adoption of these vehicles as it defines their cost, range and safety. Advances in lithium-ion battery technology are creating possibilities for electric vehicles to compete with their gasoline counterparts for the first time. However, many challenges remain, the most important of which is cost.

This thesis has three main objectives. The first is to describe the evolution of the lithium-ion battery industry up to its current state. Lithium-ion battery technology was first developed in the United States and Europe. Japanese companies were the first to adopt it and commercialize it in the early 1990s, principally for electronics products. Manufacturing capabilities spread to China and Korea in the early 2000s. By the end of the first decade of this century, Southeast Asia was dominating manufacturing of lithium-ion batteries, with 98% of global production. The United States is today investing heavily to create a domestic lithium-ion battery manufacturing capability while Asian battery manufacturers are repositioning themselves to capture the market for electric vehicle batteries.

The second objective of the thesis is to describe the current status of supply chain relations between automakers and battery manufacturers, and to understand how these relations might affect automakers' competitiveness. Three types of relationships are coexisting today: vertical integration, partnerships and outsourcing. Some automakers are developing battery packs in-house in vertically integrated organizations, others have forged partnerships with battery suppliers, while others have completely outsourced the development and manufacturing of the battery pack to an external supplier. Each model has its own advantages and drawbacks, and none would appear to be optimal for the entire industry as different automakers have different constraints and objectives. In the near future, knowledge of cell characteristics will be key to developing battery packs. While battery standardization is unlikely, as the technology matures firms will focus more on software and battery integration to establish their competitive edge.

Finally, the thesis examines the role of government policy in the industry. Many mechanisms can be used to promote the industrial development of battery technology, both on the supply-side through research funding and the support of manufacturing, and on the demand side though regulatory standards and consumer incentives.

Thesis Supervisor: Dr. Richard K. Lester
Title: Professor of Nuclear Science and Engineering

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Section 1 – Introduction

A drastic change to the current energy system has become an evident necessity. Nations across the globe are seeking to transform their energy systems to address particular concerns and priorities, including soaring demand, energy security and climate change.

One of the biggest challenges is meeting world energy demand, which is projected to increase by up to 44% by 2030 (EIA 2009c). Non-OECD countries alone will see their energy demand increase by 74%, driven by the strong growth of their emerging economies. The BRIC countries (Brazil, Russia, India and China), will account for nearly two-thirds of that growth. Pressures to meet these energy demands are likely to create energy security concerns for all countries with insufficient resources, which also include nations with more developed economies such as the United States and the European Union. With uneven distributions of fossil fuel resources such as oil and natural gas, countries will need to resort to alternative means to meet their energy demand.

Concerns about global climate change are also gaining ground. Developed countries, essentially those who initially put carbon in the atmosphere, are voicing their concerns regarding the sustainability of current energy production and consumption trends. The surge in carbon emissions following the industrial revolution could potentially have a dramatic effect on the global environment, causing temperatures increases, melting of ice caps, floods, and droughts among other ecological catastrophes, if no pre-emptive measures are taken. According to the Intergovernmental Panel on Climate Change, emission cuts of an estimated 40% below 1990 levels must be adopted by 2050 for the climate to stabilize (IPCC 2007).

In light of the recent global financial crisis, struggling nations have also identified opportunities in the energy industry to stimulate the economy through government spending and job creation to avoid financial disaster. While individual nations have different goals and priorities, the world has begun to witness a gradual transformation of its energy system, both on the supply and demand-sides.

Second only to the industrial sector, energy use in transportation[1] currently accounts for 28% of world consumption, and is projected to have increased by 45% by 2030, the fastest of all sectors (IEA 2009a). Road transport[2] uses nearly 80% of that energy, with light-duty vehicles occupying 45% alone (Figure 1). Overall transport activities consumed 51% of total oil produced in 2006 (Figure 2), and this is projected to increase to more than 56% by 2030.

With 85% of the world's population still without cars (Sperling & Gordon 2009), liquid fuel consumption is projected to grow at a significant pace, occurring mainly within rapidly expanding economies, as transportation systems become further motorized and rising living standards increase the demand for personal transportation and motor vehicle ownership. With more than one billion vehicles currently populating the planet, the global fleet is expected to double by 2030, and triple by 2050, with more than 90% of the growth driven by non-OECD countries (UNEP 2010).

Transportation is also a big part of the climate change problem. Since the 1970's, transportation-related emissions have more than doubled, increasing faster than any other sector (Sperling & Gordon 2009). Today, they account for more than one-fourth of all carbon dioxide emissions. Road transport alone is responsible for 80% of all transportation-related emissions.

The current transportation system is no longer sustainable. Its conventional energy source is becoming scarcer and more expensive, while its impacts on the environment are likely to create significant damage. Change to the transportation system is urgently needed, as economies grow, oil supplies become tighter, and climate change accelerates.

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[1] Energy use in transportation includes the energy consumed in moving people and goods by road, rail, air, water, and pipeline.

[2] Road transport includes light-duty vehicles, such as automobiles, sport utility vehicles, minivans, small trucks, and motorbikes, as well as heavy-duty vehicles, such as large trucks used for moving freight and buses for passenger travel.

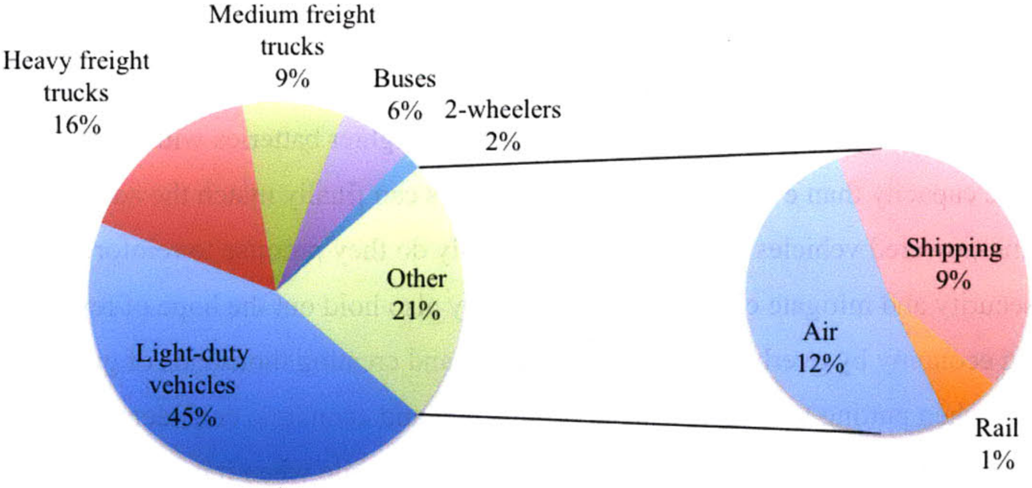

Figure 1: World Transport Energy Use in 2000, by Mode. Source: (WBCSD 2004)

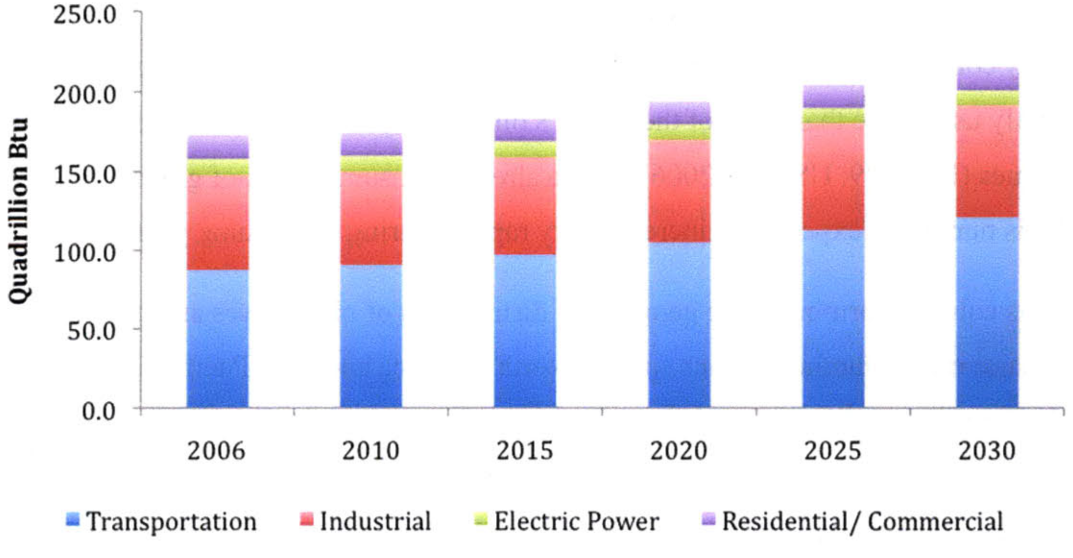

Figure 2: World Liquid Fuel Consumption by Sector, 2006-2030. Source: (EIA 2009c)

The Case for the Electrification of Vehicles

Electric vehicles[3] have recently resurfaced as a viable candidate to help solve many of the ills caused by conventional transportation. Since electric drive technology has succumbed to gasoline vehicles many times in the past, what is different this time around? Recent advancements in lithium-ion technology have produced lighter batteries with more power and storage capacity than ever before. Electric vehicles can finally match the advantages of gasoline-powered vehicles and then some. Not only do they promise to reinforce energy security and mitigate climate change, but they also hold out the hope of reviving a struggling economy by overhauling its auto industry and creating thousands of green jobs. Even when putting aside political, environmental and economic considerations, many perceive the electric car as a simply far better automobile when it comes to performance and the pleasure of driving.

Reinforcing Energy Security

In 2008, oil provided around 36% of the world's energy consumption (BP 2009). Between 2000 and 2010, the world devoured one-fourth of all the oil ever consumed throughout human history (Sperling & Gordon 2009). By 2030, world oil consumption is projected to increase by more than a quarter (Figure 2). Oil has clearly become indispensable for fueling economies worldwide. This addiction can only raise national security concerns for those countries that need it the most. The United States alone currently uses more than 25% of the world's oil, which provides 37% of the energy it consumes (BP 2009; US EPA 2006). China already consumes 10% of global production, and this number is expected to increase very rapidly during the coming years.

What is equally alarming is the geographic distribution of oil reserves and consumption. The major oil consuming regions such as North America and Asia Pacific are those with the least resources (Figure 3). North America consumes 28% of the world's oil production, while it holds only 6% of global reserves. Today, more than 55% of the oil consumed in the United States is imported, the highest level of dependence on imports in all of the country's history. Matters become even more disconcerting when one looks at

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[3] For the purpose of this thesis, electric vehicles refer to all vehicles with an electrified drivetrain including hybrid vehicles, plug-in hybrid vehicles and all-electric vehicles.

the origin of imported oil. In the case of the United States, Saudi Arabia is the second largest source of oil, followed by Venezuela, Iraq and Russia in fourth, sixth and seventh positions (Figure 4). To put it delicately, some of these countries might not have the United States' best interests at heart. Asia Pacific is in no better shape. The region consumes 30% of the world's oil and holds less than 3% of global resources (Figure 3). China, whose GDP growth is projected to average 6.4% through 2030, is expected to surpass the United States to become the world's largest economy by 2020. India is also projected to have a strong economic development with an average growth rate of 5.6%, driving energy demand to double by 2030. The two countries combined will have grown from 10% of world energy consumption in 1990 to more than 28% in 2030, compared to 17% for the United States (EIA 2009c).

In the United States, transportation activities account for 28% of national energy consumption (EIA 2009a), of which 94.3% are powered by petroleum (Davis et al. 2009). The transportation sector alone consumes more than 70% of the oil used in the United States. Passenger vehicles and light trucks consume more than half of it.

China, the fastest-growing automobile market and already the world's second-largest, is expected to overtake the United States as the world's biggest by 2030 (Gao et al. 2008), with India coming in third. It is estimated that the combined Chinese and Indian population of 2.4 billion people will drive the global automobile market with a 7 to 8% yearly growth compared to the 1 to 2% growth in the United States and Europe (Davis et al. 2009). By then, China alone would have more than 287 million vehicles – approximately 30% of the global vehicle fleet – and will need to import 6.2 billion barrels of oil to fuel them.

The consumption of oil on such a large scale raises yet another issue. Oil price increases and price volatility have destabilized economies worldwide for many of the past decades. Just in the last 10 years, oil prices have ranged between $20 and $80 a barrel, before rising to more than $100 during 2008 and reaching an all time high of $147 a barrel in July of that year (Figure 5). Short-term volatility is also an issue. In 2008 oil prices went from $90 a barrel to $147 in July and then back down to $30 four months later. World crises including wars, political pressures, even missile tests, all affect the spot price of oil, which varies on a daily basis.

The use of liquid fuels in the transportation sector has thus far proven to be irreplaceable, despite the many ills that come with it. The fundamental advantage of liquid fuels is their very high energy content and ease of storage and transportation, when compared to other fuel alternatives. Gasoline contains 60 to 300 times more energy than electric batteries per unit of mass and 3,000 times more than hydrogen gas per unit of volume. Its liquid state also makes it very practical to transport and store using pipes, trucks, and tankers. In contrast, hydrogen would require a completely pressurized infrastructure that would also bring about a whole series of safety and practicability issues. It has also been suggested that the current electric infrastructure is not well suited to the demands of an electric vehicle fleet[4].

Recent developments in lithium-ion battery technology are challenging the status quo. Battery-powered electric vehicles substituting for gasoline and diesel could be a potent approach to mitigate consumption of oil and decrease the world's dependence on it. By using electricity as a transportation fuel, energy generation in the form of combustion under the hood of the car would now migrate to the utility power plant. This would open up a variety of energy alternatives including coal, which is more abundant in oil-deprived regions such as North America and Asia Pacific, nuclear energy and even clean renewable energy sources such as solar, wind and hydro.

As a result, many countries, including the United States and China, are exploring the electrification of their car fleets as a promising path to energy and national security. While electric vehicles might not serve to slow energy demand, they will enable countries to better tune their energy supply mix in a direction that is less dependent on a scarce and volatile commodity. Electric vehicles could also address another issue, one that transcends nations' borders, and affects the global population.

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[4] The issues and challenges pertaining to the electric infrastructure will be discussed in Section 2 – An Introduction to Battery Technology and Electric Vehicles

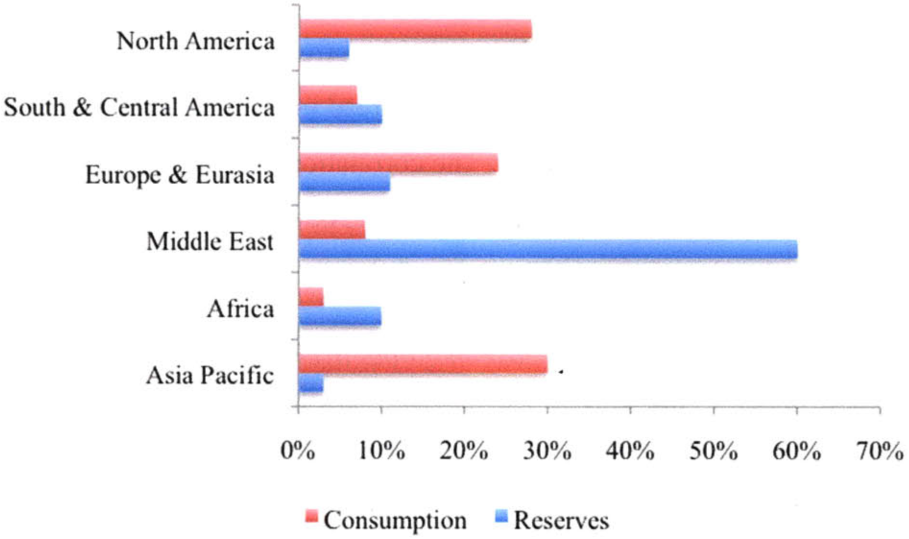

Figure 3: Oil Reserves and Consumption by Region in 2008. Source: (BP 2009)

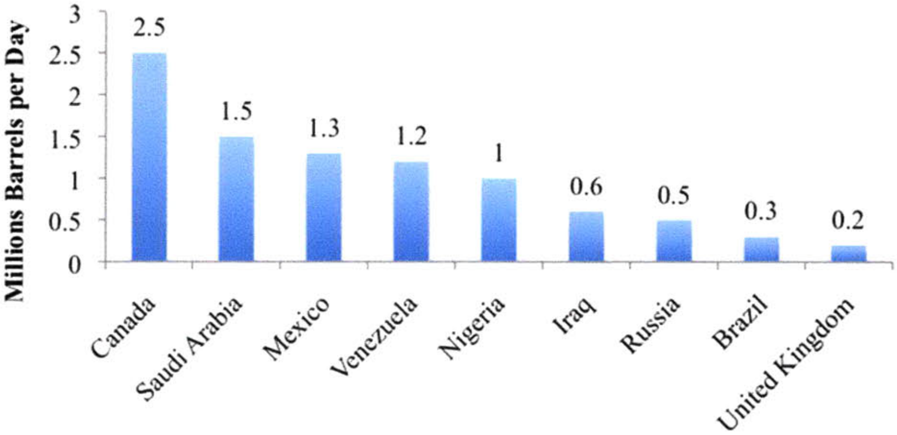

Figure 4: U.S. Petroleum Imports by Country of Origin, 2008 (EIA 2009a)

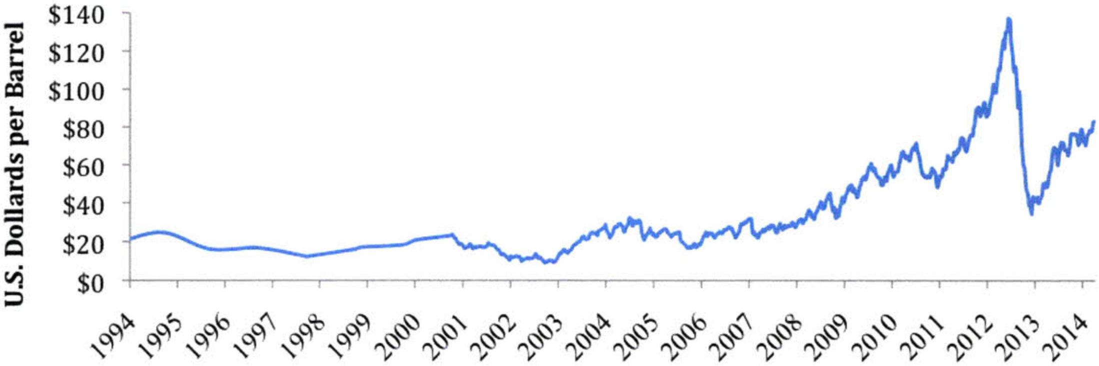

Figure 5: Oil Spot Price FOB Weighted by Estimated Export Volume. Source: (EIA 2010)

Mitigation of Climate Change

Warming of the global climate system is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level (IPCC 2007). The correlation between greenhouse emissions and global climate change is described in the Fourth Assessment Report by the Intergovernmental Panel on Climate Change as follows:

> *"Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations".*

The largest growth in anthropogenic greenhouse gas emissions since the 1970's has come from energy supply for transport and industry. Combustion of fossil fuels in the transportation sector alone account for 22% of total emissions (IEA 2009a), and emissions from this source are expected to increase by 80% by 2030 (IEA 2009b). Road transport alone accounts for 16% today (Figure 6).

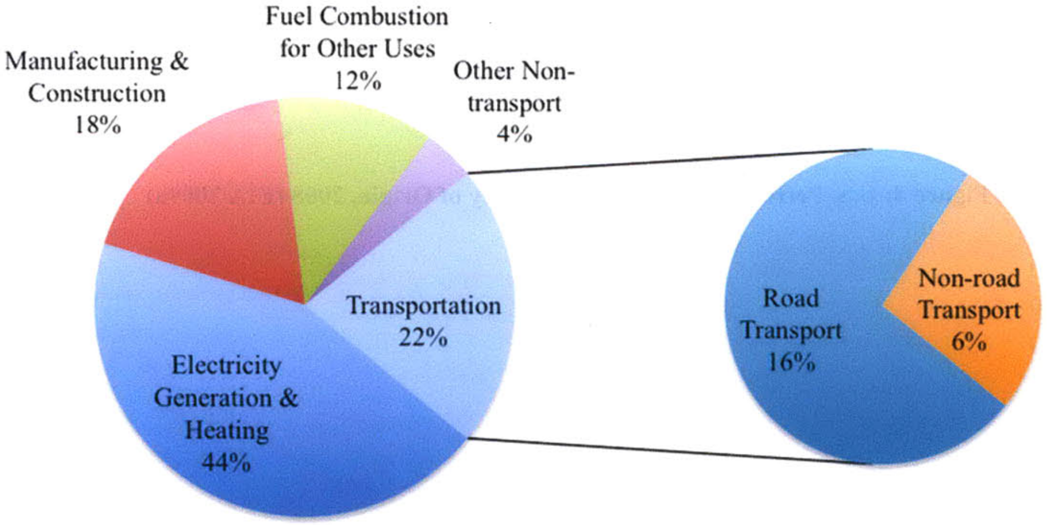

Figure 6: Anthropogenic Carbon Dioxide Emissions by End-use. Source: (OICA 2007)

The United States is still the biggest market for transport vehicles, and thus the biggest contributor to transport emissions in the world. In 2008, greenhouse gases emitted from the transportation sector amounted to 28% of U.S. emissions, and accounted for nearly half of the nation's total increase in greenhouse emissions since 1990 (EIA 2009b). As Table 1 indicates, passenger cars and light-duty trucks running on gasoline or diesel account for nearly 58% of total transportation-related emissions. Since the early 1970's, there have been more registered vehicles than drivers and more than two vehicles per household in the U.S. To make matters worse, the average fuel economy of new vehicles sold annually gradually declined between 1990 and 2004. This was driven mainly by the increasing market share of light duty trucks, which grew from about one-fifth of new vehicle sales in the 1970's to slightly over half of the market by 2004. With increasing fuel prices since 2005, the momentum of light duty truck sales has lessened, improving the average new vehicle fuel economy with the increasing market share of passenger cars.

The United States is not the only source of concern in this regard. When China overtakes the U.S. as the biggest car market, as is expected by 2030, its passenger vehicles fleet could be responsible for generating as much as 20% of global passenger vehicle emissions (Gao et al. 2008). India, by then the third largest car market, will see its emissions tripling by 2030.

The IPCC has stated that vehicle fuel economy can improve by up to 50% (IPCC 2007). While further development of current combustion technology can provide some improvements in fuel efficiency, environmental gains from such measures are likely to be offset by increased travel and population. More drastic changes including alternative fuels and more efficient powertrains have to be considered. Electric vehicles are one of the strongest contenders for clean transportation.

Fuel/Vehicle Type	**CO_2 Emissions** *($Tg\ CO_2\ Eq.$)*
Gasoline	**1,129.4**
Passenger Cars	593.6
Light-Duty Trucks	486.1
Medium/Heavy-Duty Trucks	33.7
Buses	0.4
Motorcycles	2.1
Recreational Boats	13.5
Diesel	**441.9**
Passenger Cars	3.9
Light-Duty Trucks	26.7
Medium/Heavy-Duty Trucks	354.5
Buses	10.3
Rail	43.2
Recreational Boats	0.9
Ships and Other Boats	2.2
International Bunker Fuels	9
Jet Fuel	**153.6**
Aviation Gasoline	**2**
Residual Fuel Oil	**21.4**
Natural Gas	**35.8**
LPG	**1.2**
Electricity	**4.7**
Total	**1,925.1**

Table 1: U.S. Greenhouse Gas Emissions from Fossil Fuel Combustion in Transportation Sector, 2008. Source: (US EPA 2006)

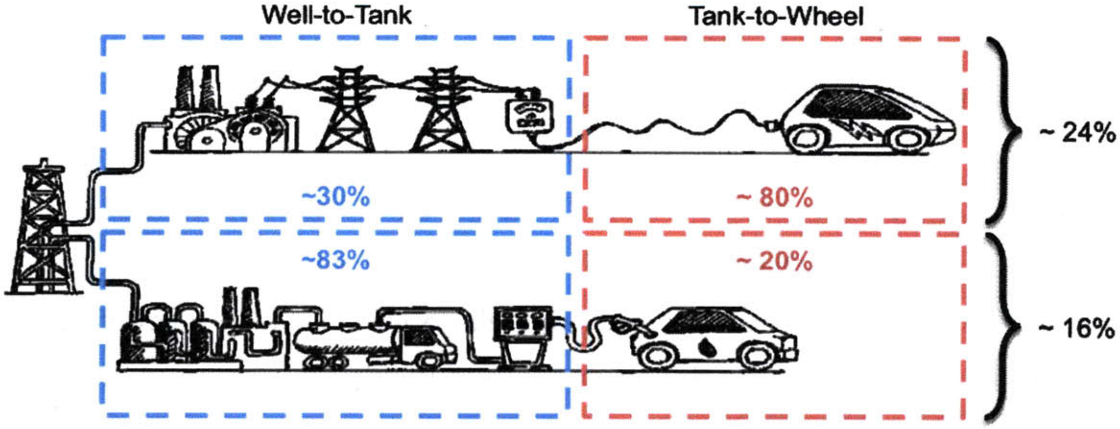

Figure 7: Well-to-Wheel Efficiencies for Gasoline and Electric Vehicles. Source: (NESEA 2008)

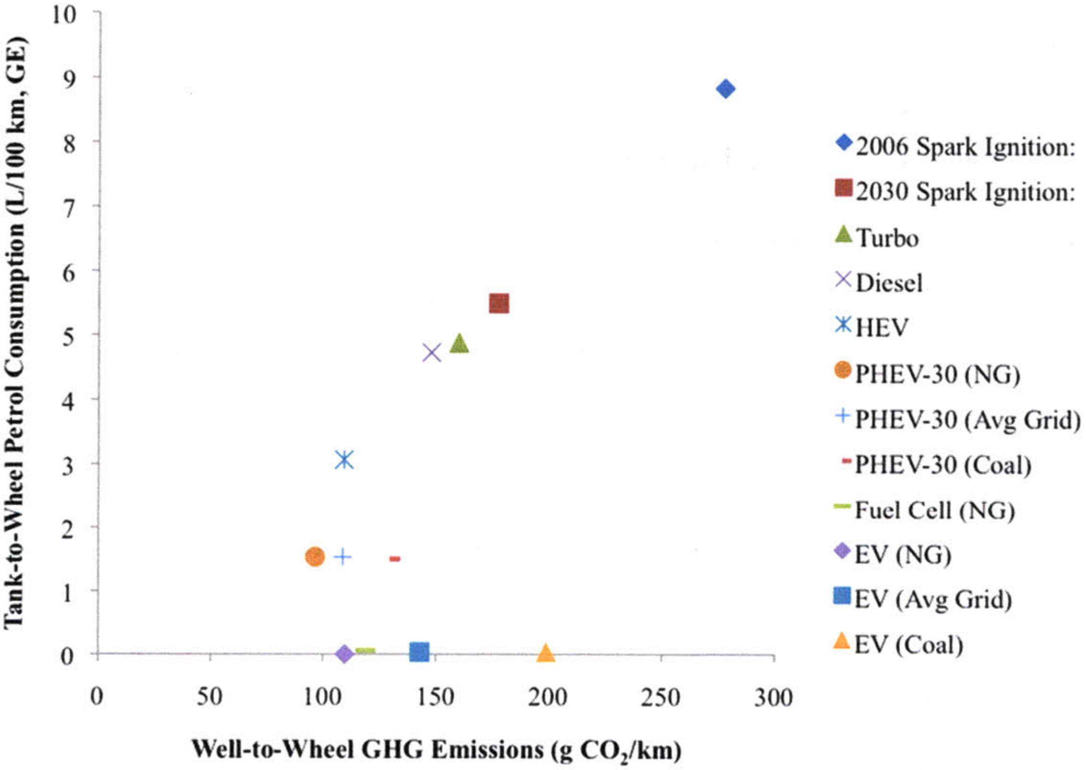

Figure 8: Petroleum Consumption and GHG Emissions of Various Propulsion Systems in 2030 Over the Combined and Adjusted HWFET/FTP Drive Cycle. Source: (Heywood 2010)

Internal combustion vehicles running on gasoline or diesel waste more than two-thirds of the fuel they burn and emit around 20 pounds of carbon dioxide into the atmosphere for every gallon of fuel they burn. Electric vehicles have a drivetrain that can be up to three times more efficient (in the case of all-electric vehicles). Even when looking at well-to-wheel efficiencies, electric vehicles have an efficiency of around 24% while gasoline vehicles have an efficiency of 16% (Figure 7). Electric vehicles have therefore a large potential of reducing greenhouse gas emissions (Figure 8). Displacing the generation of energy from under the hood to large power plants allows the use of more efficient and thus cleaner generation processes. In fact, any form of electrification proves to be more effective in reducing energy consumption and GHG emissions than improved combustion technology (Figure 8). Using the average grid to power electric vehicles would cut well-to-wheel emissions by almost half. Even when electric vehicles are recharged from coal-powered electric generators, emissions would still be reduced. Emissions can be even further decreased by integrating cleaner forms of electrical power generation, such as hydropower, nuclear, solar or wind, or retrofitting existing plants, and implementing carbon capture and sequestration measures.

Aside from the impact on overall emissions, displacing the tailpipe from underneath the car to the electricity plant also has the local benefit of reducing smog. Cities such as Los Angeles, Mexico City, Athens, Milan, Cairo, Kolkata and Beijing suffer from some of the worst air pollution in the world. The use of electric vehicles would eliminate local emissions and contribute towards healthy air.

The pursuit of electrification is also driven by economic motives.

Stimulating Economic Growth

Car manufacturing is one of the world's most important industries, with a total turnover of around $2.6 trillion, equivalent to the 6th largest economy in the world (OICA 2007). In the United States, the auto industry contributes 3 to 4% of total GDP and employs over one million people (Hill et al. 2010). The industry is also a huge consumer of goods and services from many other sectors and thus contributes to a net employment impact in the U.S. economy of nearly 8 million jobs. Approximately 4.5% of all American jobs are supported in one way or another by the auto industry.

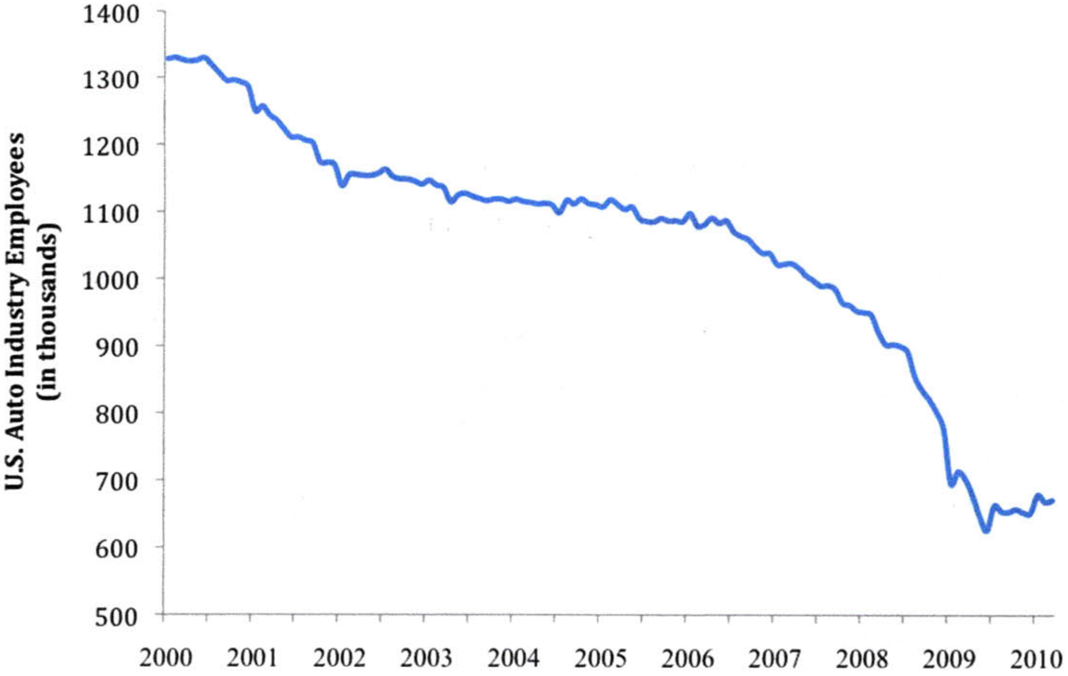

Figure 9: United States Employment in the Automobile Industry, 2000-2010. Source: (Bureau of Labor Statistics 2010)

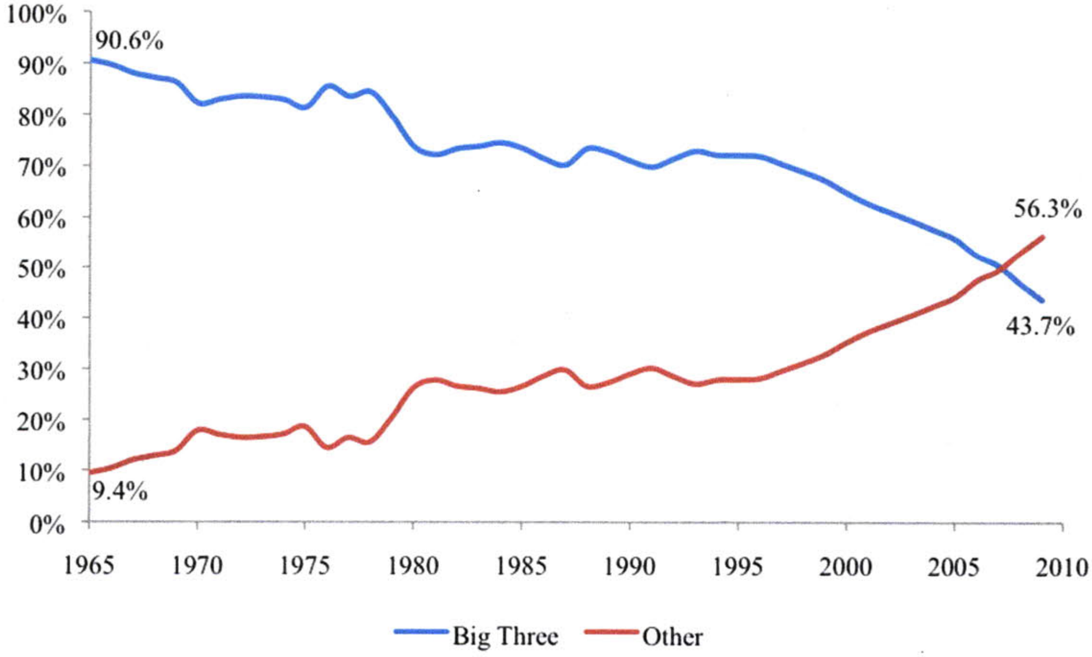

Figure 10: U.S. Motor Vehicle Market Share, 1965-2009. Source: (Wards Auto 2010)

With the recent global financial crisis, many leading economies have found themselves struggling with a declining GDP, debt burdens, and rising unemployment. The automobile industry has been badly affected. In the United States, the health of the industry quickly deteriorated as the recession took hold in 2008, choking off credit to automakers, suppliers and consumers. By the end of the year, two of Detroit's Big Three were in dire straits, while the entire U.S.-based auto producing industry was operating facilities at less than 50% capacity utilization (Hill et al. 2010). This ramp-down in production affected not only the OEM's, but suppliers as well, as they cut production and, along with the OEM's, laid off employees. Employment in the auto industry dropped from 950,000 in beginning of 2008 to 626,100 in June 2009 (Figure 9), a decline of 34% in 18 months.

As part of a nationwide plan to revive the economy and restore employment, the United States government identified an opportunity to restructure an industry that has been struggling for decades (Figure 10). The strategy of building large gas-guzzling SUV's with higher profit margins was no longer sustainable in the face of smaller fuel-efficient overseas brands, especially after continuously increasing gasoline prices since 2003. Efforts on several fronts are now being pursued to reinvent the auto industry in the United States by focusing development on electric-drive vehicles.

In 2009 the U.S. government invested more than $17 billion to bail out General Motors and Chrysler, after both companies went under. The deal was accompanied with explicit instructions to develop the next generation of green vehicle technology relying mainly on electric drivetrains. General Motors will be the first American automaker to develop and market a plug-in hybrid vehicle[5], the Chevy Volt, which is expected to be launched in 2011. The U.S. Department of Energy was already pursuing its own Advanced Technology Vehicles Manufacturing Loan program, a $25 billion program dedicated to accelerate the development of electric-powered cars and improve battery technology.

The American Recovery and Reinvestment Act introduced by the Obama administration and enacted by Congress in 2009 will invest more than $2.4 billion in grants to accelerate

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[5] The first automaker to mass-market a plug-in hybrid vehicle is Chinese BYD Auto, which launched the F3DM in 2008.

the manufacturing and deployment of the next generation of batteries and electric vehicles in the United States. Spanning over 20 states, 48 new advanced battery and electric drive components manufacturing and electric drive vehicle deployment projects are projected to create or retain tens of thousands of jobs.

States are also aiming to create green jobs for the electric vehicle and battery industry, by providing tax credits. In total, more than $5.3 billion in electric vehicle-related projects have been started or announced in Michigan. These projects are expected to create thousands of jobs. While electric cars mostly served as concepts revolving on shiny platforms in auto shows in the past, this time around they might just be the cars that could save Detroit.

Other countries are also investing significantly in developing local electric vehicle industries. By 2006 China had become the world's third largest automotive vehicle manufacturer, after the U.S. and Japan, and is expected to become the world's largest by 2020, and the Chinese government aims to make the country one of the leading producers of hybrid and all-electric vehicles by 2015, and the world leader in electric cars and buses after that (Bradsher 2009). Japan, which has so far proven to be the market leader in green car technologies, is also working hard to preserve its edge.

Improving Car Attributes

Electric-drive vehicles offer many benefits over gasoline-driven cars. Replacing an internal combustion drivetrain with an electric one improves car performance while minimizing some of the operating costs thanks to superior efficiency and ease of maintenance.

While gasoline engines can only increase torque progressively, electric motors can provide instantaneous high torque, thus enabling much faster acceleration than gasoline engines. For example the Tesla Roadster Sport equipped with a 288 horsepower engine can reach 60 mph in 3.7 seconds while the Porsche Boxter Spyder – a fairly comparable car – with a 320 horsepower engine reaches 60 mph in 4.3 seconds.

As mentioned earlier, electric drivetrains are overall much more efficient than their gasoline counterparts. Electric vehicles can reach drivetrain efficiencies of 80%, while gasoline cars have efficiencies around 20%. Electric vehicles are particularly more efficient in city driving conditions where idling situations are frequent. Even when the vehicle is at a complete stop, gasoline engines are continuously running, dissipating all the energy produced. On the other hand, electric motors have the benefit of shutting off when the vehicle reaches a complete halt, thus consuming no energy at all in these situations. Electric motors also allow for regenerative braking, which converts braking energy back into stored electricity when the car is decelerating. This feature, which is particularly effective for city driving, increases even further the overall efficiency of an electric vehicle. These efficiency gains allow for better well-to-wheel efficiencies, enabling less energy use and fewer emissions.

Electric vehicles also allow a better driving experience. Since they are powered by electricity, electric drivetrains are easier to control through power electronics compared to combustion drivetrains, which rely on mechanical energy. They therefore allow for better and easier traction control. The lack of a combustion engine and a mechanical drivetrain allows for virtually no noise and vibration, making the ride much smoother and more comfortable.

Looking beyond the initial purchase price of an electric vehicle, the operating costs are much more advantageous. In terms of fuel costs, an electric vehicle could typically cost less than 2 cents per mile to drive, compared with 12 cents a mile on gasoline at a price of $3.60 a gallon. Section 2 – An Introduction to Battery Technology and Electric Vehicleswill provide a more detailed analysis of the economics of an electric vehicle. Aside from the cost of fuel, maintenance costs are also reduced for all-electric vehicles as they lack an internal combustion engine, a gearbox and fluids.

Because of the factors mentioned above, electric vehicles seem to have a promising outlook. Many market researchers and consulting firms have published reports that forecast the deployment of electric vehicles. The Boston Consulting Group have rather bullish expectations, forecasting that 26% of new cars sold in 2020 (14 million vehicles) in the major developed markets (China, Japan, the U.S. and Western Europe) will have electric or hybrid powertrains (Boston Consulting Group 2009b). This would require a compounded annual sales volume growth of around 30%. Another study by McKinsey &

Company forecasts that the total market for electric vehicles in North America, Europe and Asia will reach $80 to $120 billion by 2030, assuming a moderate 5 to 10% penetration of electric vehicles by then (Gao et al. 2008). Disparities in deployment forecasts indicate that while electric vehicles are expected to have a certain presence, the rate of growth remains unclear. The adoption of electric vehicles depends on a multitude of factors with complex interactions that cannot be entirely predicted. These include the evolution of the learning curve of lithium-ion batteries, which inevitably affects the cost and range of electric vehicles. Fuel prices will have a very important role as well in determining the cost-effectiveness of these vehicles. Finally, customer adoption and their willingness to change their driving behavior must also be considered. Given the uncertainty of some of these parameters, one needs to be critical when looking at such market growth forecasts, for electric vehicles.

The Battery: A Critical Component

Electric vehicles have clearly many advantages as pointed out above. Their absence thus far from roads and highways is largely due to limitations in battery technology. Essentially, the battery determines the overall characteristics of an electric vehicle; it defines how much it costs, how far it can travel and how safe it is. Previous battery technologies failed to provide the required specifications, particularly in terms of driving range. However recent developments in lithium-ion battery technology have eliminated these limitations. For what may be the first time in the history of the electric vehicle, these cars are able to compete with their gasoline counterparts by showcasing competitive performance while providing even further benefits. Nevertheless, batteries will continue to dictate the cost, range and safety of these vehicles.

Table 2 lays out the battery characteristics of three different electric vehicles: the Tesla Roadster, the Nissan Leaf and the Chevrolet Volt.

		Tesla Roadster	**Nissan Leaf**	**Chevrolet Volt**
Vehicle	**Type**	All-electric	All-electric	Plug-in
	Cost	$109,000	$32,780	$38,000*
	Range	240 miles	100 miles	40 miles
Battery	**Energy**	56 kWh	24 kWh	16 kWh
	Weight	992 lbs	480 lbs	400 lbs
	Cost	$36,000* (33%)	$18,000* (55%)	$10,900* (29%)
	$/kWh	$640/kWh	$750/kWh	$680/kWh
	$/Mile	$150/mile	$180/mile	$273/mile
	Mile/lb	0.24 miles/lb	0.21 miles/lb	0.1 miles/lb

* estimated

Table 2: Battery Characteristics of the Tesla Roadster, Nissan Leaf and Chevrolet Volt.

Battery cost probably remains the major issue for electric vehicles. Batteries are estimated to account for up to half the cost of an electric vehicle, at least in the early stages of battery and electric vehicle development. For example, the Tesla Roadster priced at $109,000 is estimated to have a battery that costs more than $30,000. The Nissan Leaf has a price tag of $32,780 and its battery is estimated to cost just under $18,000, more than 50% of total cost of the vehicle.

The range of an electric vehicle typically depends on the amount of energy per unit mass or volume that can be stored in its battery. For a given weight, lithium-ion batteries can store up to three to five times the energy compared to lead-acid batteries used in previous electric cars. Lithium-ion batteries can thus allow for ranges of 100 miles and above with a much lighter and smaller battery. The Nissan Leaf is equipped with a 24-kWh battery that weighs 480 lbs battery and runs for 100 miles on a single charge, while the Roadster, with a 53-kWh battery can run for more than 200 miles on a single charge. Both vehicles have a mile/lb performance between 0.21 and 0.24. Remarkably, the Chevrolet Volt has a mere 0.1 mile/lb of battery. This is mainly due to the oversized design of the battery pack. While the pack contains 16 kWh of energy, only 8.8 kWh of that is effectively used. GM engineers have elected to opt for an oversized design in order to ensure a battery life of at least 10 years.

Lithium-ion batteries, which are prone to overheat, also raise many safety concerns. We have all seen or heard of incidents involving lithium-ion laptop batteries bursting into flames. Since electric vehicles will be incorporating batteries with similar technology, many efforts are being invested to design safe and reliable battery packs, especially given that vehicles are prone to accidents and crashes. Tesla Motors has designed a complex architecture in its Roadster battery pack with many safety features, including active and passive measures, as well as various mechanical and electrical mechanisms. The Chevy Volt's battery design includes multiple computers that run hundreds of tests to monitor the cells and the overall battery to confirm everything is working correctly.

Batteries are clearly the most critical component in an electric vehicle. They will either make or break the electric vehicle industry. Automakers will therefore have to pay careful attention when picking their battery suppliers, as the latter will have tremendous leverage on their products. Batteries will give car companies their competitive edge. They will determine how fast a car can accelerate, how far it will go on a single charge, how quickly it can recharge, and since it accounts for as much as half the cost of an all-electric vehicle, how much it costs. How automakers go about selecting the battery system for their vehicles and their interactions with battery suppliers will be instrumental in defining their competitiveness.

The main purpose of this thesis is to better understand the supply chain relations between battery suppliers and automakers and their effect on the competitiveness of automakers. However, before tackling these interactions, it is important to learn and understand the two industries involved, the electric vehicle and battery industries. This will be covered in section 2. Section 3 covers the organization of the lithium-ion battery industry, its historical development as well as current industry trends. Section 4 will focus on the supply chain relations between battery suppliers and automakers. Section 5 will cover the role of policy in the industry and what governments have accomplished so far. Finally, section 6 will present concluding remarks and offer an outline for potential future work.

Section 2 – An Introduction to Battery Technology and Electric Vehicles

Before engaging in a discussion of the battery industry and its interaction with the electric vehicle supply chain, it is important to understand the technologies involved in both industries. The following section provides a brief introduction to battery and electric vehicle technologies that will allow for a richer and more informed discussion of the subsequent topics of interest.

An Introduction to Battery Technology

Since the inception of the automobile, batteries have played a key role in the development and adoption of both electric cars and gasoline-run vehicles. In order to concretize the importance of the battery to overall vehicle performance, the following section will describe how batteries work, how they are evaluated, and the different types of batteries used in the automotive industry.

How Batteries Work?

A battery is an electrochemical storage device that stores electrical energy in the form of chemical potential between its positive and negative electrodes. The key components of an elementary battery are the anode and cathode, which form the electrodes, the electrolyte and the separator (Figure 11). Upon discharge, chemical reactions initiate a flow of electrons from the anode to the cathode, which produces an electric current in the external circuit. The separator allows for positive charges to migrate from the anode to the cathode in the electrolyte without the passage of other molecules.

Batteries are classified into two broad categories, primary batteries which host irreversible reactions and can thus be used only within a single cycle, and secondary batteries whose reactions are reversible and can be charged and discharged numerous times. Secondary batteries are charged by applying an external electric current. The current triggers the chemical reactions to operate in reverse, bringing the battery back to a state of high energy. Given the cyclical nature of automotive applications, batteries used in automobiles are of course rechargeable.

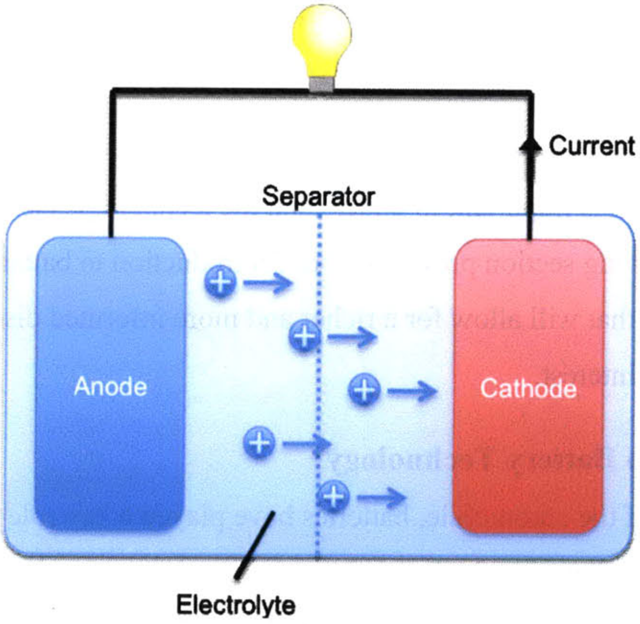

Figure 11: Battery Schematic During Discharge Cycle

Evaluating Battery Technology

Batteries are generally described or evaluated using a set of parameters or metrics that reflect performance. The key parameters generally used to evaluate battery technologies for automotive applications are: energy density, power density, life span, thermal management, and cost.

Energy density

If a battery is regarded as a black box that contains energy, energy density is a measure of the amount of energy that can be stored in that box, typically specified in units of mass (Wh/kg) or units of volume (Wh/l). This is of particular importance for electric vehicles because energy density dictates the weight and volume of a battery for a given amount of energy, which ultimately impacts how far a vehicle can be driven on a single charge.

Power Density

Again, looking at a battery as a black box, power density indicates the rate at which energy can be extracted from that box. This quantity is typically specified in units of mass as "W/kg". Batteries for electric vehicle applications typically require high currents to drive the motor. Thus, high power densities are generally desired.

Life Span

Given the cyclic nature of electric vehicle applications, the materials and components involved in batteries are subject to failure and degradation over time. Reduction in cycle life usually occurs due to a loss of active materials after a large number of cycles. The lifetime of a battery might also be compromised if the battery goes through deep discharging where most of the energy stored is drained from the medium. This is particularly relevant for some designs of electric vehicles, which rely on deep discharge cycles. Battery life might also be shortened if the battery operates in extreme temperatures, or is subjected to fast charging and discharging.

Thermal Management

High power batteries for electric vehicles are prone to rapid heating, which could ultimately lead to an explosive discharge of energy. This thermal runaway occurs during uncontrolled charging or from electrical or physical abuse of the cell. These risks are currently addressed by designing an enclosure that serves as a physical barrier. Ultimately, it would be tremendously beneficial to introduce inherent safeguards that prevent explosive releases of energy altogether.

Cost

With an intricate manufacturing process and a variety of chemistries proposed, cost emerges as a major concern. Even if all other performance metrics are optimized, if battery costs[6] remain high, electric vehicles will not be able to compete with gasoline cars and mass deployment will be unlikely.

Battery Chemistries

While the fundamental physical principles remain the same, the nature of reactants and materials present in batteries has changed over time, leading to a variety of chemistries that offer continuous improvement in characteristics and performance. Battery chemistries used in automotive applications are lead-acid, nickel metal hydride and lithium-ion.

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[6] Cost drivers in lithium-ion battery manufacturing will be brought up later in section 2 and the economics of battery-powered electric vehicles will be discussed in further detail in section 5.

Lead-acid

Lead-acid batteries are the oldest type of rechargeable batteries. They powered the first electric vehicles back in the late 1800's and enabled the use of electric starters in gasoline-powered vehicles, which facilitated their adoption in the early 1900's. Since then, they have been used in all vehicles running on internal combustion engines to provide starting, lighting and ignition (SLI) functions. Their main attributes are low cost, reliability and abundance, while their drawbacks are low energy densities and their inability to perform deep discharges.

Nickel Metal Hydride

Nickel metal hydride batteries (NiMH) were introduced in the 1990's and soon became the most popular chemistry for hybrid vehicles, thanks to their higher energy density and low cost. This chemistry is also considered to have a more positive impact on the environment since its does not contain any lead or other toxic elements like its predecessor (lead-acid). Nickel metal hydride batteries have quite a controversial history. The basic science behind this chemistry was developed by Stan Ovshinsky in the United States, who invented and patented the NiMH battery and founded Ovonics Battery Company in 1982. General Motors then bought the patents in 1994 before selling them to Texaco, which was soon after acquired by oil giant Chevron in 2001. That same year, the company filed a patent infringement suit against Toyota's battery supplier, Panasonic, ultimately succeeding in restricting the use of its large format NiMH batteries to specific transportation applications. In 2003, Ovonics was restructured into Cobasys, a fifty-fifty joint venture between ChevronTexaco and Ovonics, now known as Energy Conversion Devices. The discontinuation of the EV1 electric vehicle program by GM during the 1990's was partially attributed to the lack of availability of NiMH batteries. It seems that Ovonics was only willing to sell smaller NiMH batteries for hybrid electric vehicles applications, and required large orders (more than 10,000) for large-format batteries. In her 2007 book *Plug-in Hybrids: The Cars that Will Recharge America*, Sherry Boschert concludes: "it's possible that Cobasys (Chevron) is squelching all access to large NiMH batteries through its control of patent licenses in order to remove a competitor to gasoline. Or it's possible that Cobasys simply wants the market for itself and is waiting for a major automaker to start producing plug-in hybrids or electric vehicles" (Boschert

2007). During the late 1990's, Toyota and Honda became the earliest adopters of nickel metal hydride batteries for hybrid vehicles, which were supplied by Japanese manufacturers Panasonic and Sanyo.

Lithium-ion

Lithium-ion batteries were first introduced into the consumer electronics sector in the early 1990's, enabling light and durable handheld mobile phone devices, laptop computers, music players, and many other products. The chemistry quickly gained popularity as it exhibited much higher energy and power densities than its predecessors, and had a superior cycle life and a low self-discharge (Figure 12). As such, lithium-ion batteries are undoubtedly the chemistry of choice for next-generation electrically propelled light motor vehicles. While lead-acid and nickel metal hydride chemistries are too heavy to be considered for electric vehicles requiring large batteries, lithium-ion batteries would be ideal thanks to their light weight and high power.

Lithium-ion batteries all have lithium graphite as the anode and a different material for the cathode consisting of a layered-oxide. Each combination of materials has its own advantages and disadvantages in terms of the performance metrics described above. The most prominent chemistries for automotive applications are lithium-nickel-cobalt-aluminum (NCA), lithium-nickel-manganese-cobalt (NMC), lithium-manganese-spinel (LMO), lithium titanate (LTO), and lithium-iron phosphate (LFP). The technology that is most prevalent in consumer electronics applications is lithium-cobalt oxide (LCO), which is generally considered unsuitable for automotive applications due to inherent safety risks. Sony in fact had to recall many of its laptop batteries in 2006 and 2008 after some overheated and caught fire or exploded (Bradsher 2009). As Figure 13 shows, there is no ultimate chemistry that supersedes others along all parameters. A chemistry that optimizes safety, for example, compromises other dimensions such as specific energy and power —as is the case with lithium-iron phosphate (LFP). The best performing chemistries are either less safe (LMO) or too expensive (LTO). While it is generally accepted that lithium-ion batteries are the highest performing commercial batteries, they still exhibit some limitations that need to be overcome. These limitations will be discussed at the end of section 2.

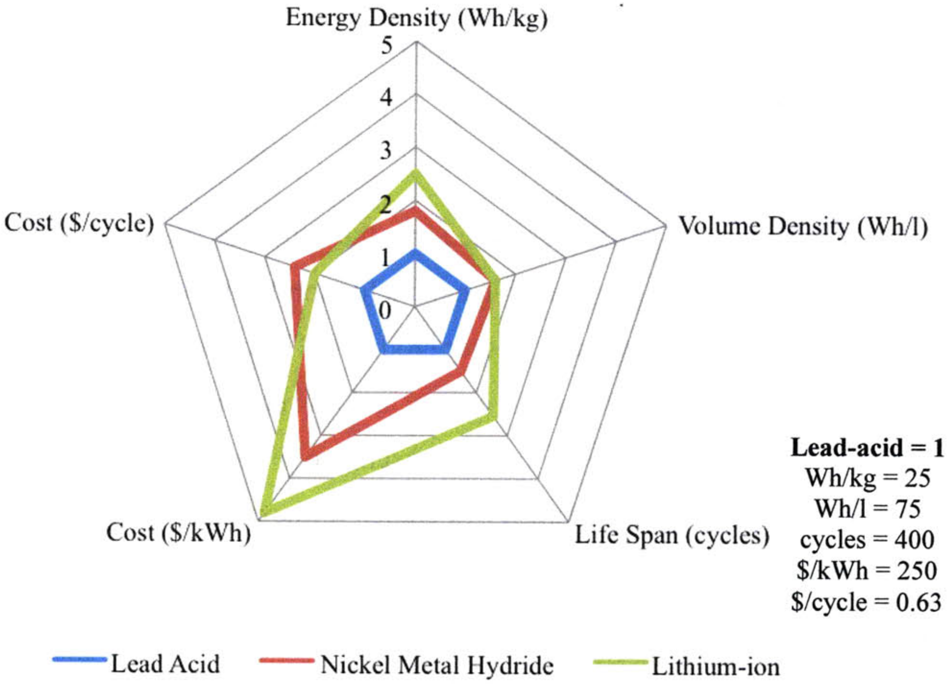


Figure 12: Comparison of Lead-acid, Nickel Metal Hydride and Lithium-ion Batteries. Source: (Axion Power 2009)

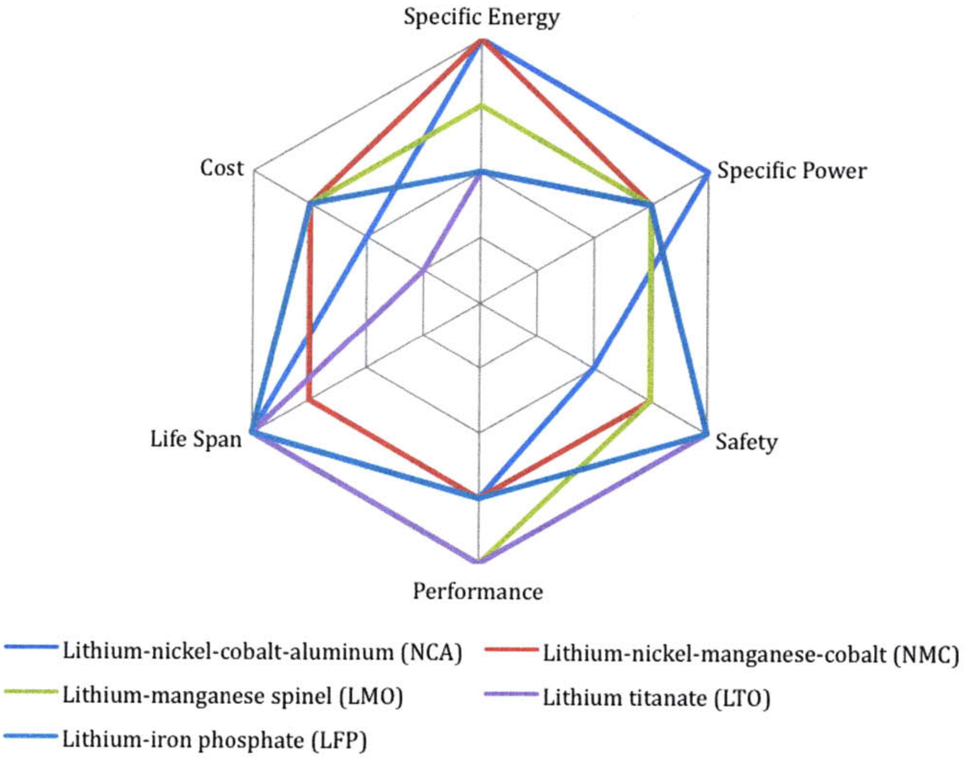


Figure 13: Comparison of the five principal lithium-ion battery chemistries. Source (Boston Consulting Group 2009a)

An Introduction to Electric Vehicles

Electric cars first surfaced during the 19th century and remained legitimate alternatives to the gasoline-powered internal combustion engine up until the 1920's, when the latter crushed all other opponents and ruled roads and highways for the remainder of the 20th century. Despite their many advantages, the defeat of electric cars was mostly attributed to weak batteries that were too heavy and stored little energy (Armand & Tarascon 2008). This section will first describe brief the history of electric vehicles and then outline the various types of electric vehicles.

History of Electric Vehicles: The Comeback

While early electric car models appeared as early as the 1830's, electric vehicles in the proper sense could not be developed until a suitable battery technology was established. That occurred in 1859 when French physicist Gaston Planté developed the first lead-acid battery. In 1881, Camille Faure, a fellow countryman, would develop a more efficient and reliable design with a greater capacity, which could be manufactured at industrial scale. These breakthroughs in battery technology are undoubtedly responsible for paving the way for electric vehicles.

The first electric drive cycle consisting of a two-wheeler was showcased at the 1867 World Exposition in Paris. France and Britain soon became the first adopters of electric vehicles, while other European countries followed suit. It wasn't until the late 1800's that the Americans showed interest in electric transportation. The first electric car to make its debut in the United States was in 1891, in Des Moines, Iowa. William Morrison had designed a six-passenger wagon capable of reaching speeds up to 14 miles per hour. Interest picked up when A.L. Ryker introduced electric tricycles to the U.S. in 1895. By then, Europeans had already adopted electric transport for more than fifteen years. In 1897, electric vehicles were commercialized in the U.S. when the Electric Carriage and Wagon Company of Philadelphia built an electric taxi fleet for New York City.

As they became commercially available, electric cars outsold all other types of vehicles, proving to be the preferred mode of transportation. Compared to its gasoline counterpart, the electric car did not have any vibration, noise or smell, nor did it require the manual effort to start and change gears. Steam cars were also inconvenient as they had a shorter range before requiring water and start-up times could take as long as 45 minutes on a cold day. Not only were they easy to operate and convenient to service, electric cars were also superior when it came to performance. In fact, they set many speed and distance records during that era. In 1899, Camille Jenatzy was able to break the 100 kilometers per hour (62 miles per hour) speed barrier in his rocket-shaped electric vehicle. Ferdinand Porsche's all-wheel drive electric car also set several records. The vehicles produced at that time were mostly elaborate, bulky carriages designed for the rich. While basic electric cars cost under $1,000 in 1900 dollars (about $26,000 today), with expensive materials and fancy interiors, electric vehicle price tags averaged $3,000 (about $78,000 today) by 1910.

Many hybrid models were also introduced during that period. The first hybrid model, the Mixte, was designed by Ferdinand Porsche in 1900 and showcased a year later at the Paris Auto Show. The car could travel nearly 40 miles on battery alone, before using the Daimler gasoline engine to extend its range. Hybrid buses were also seen in England in 1901 and hybrid cars competed in races in New England in 1902. Another gasoline-electric hybrid car was proposed in 1917 by the Woods Motor Vehicle Company of Chicago. Alas the hybrid was a commercial failure, due to very low speeds and difficulty to service.

Electric cars enjoyed tremendous success and production peaked in 1912. Soon thereafter, the once-revered vehicle began succumbing to the rise of the gasoline-powered car.

Henry Ford revolutionized the automobile industry when he introduced the model T in 1908, the first internal combustion vehicle to be mass-produced. Even though the first combustion engine was developed as early as 1867 by Nikolaus Otto, initial gasoline vehicles were expensive, unpleasant to drive, and hard to maintain. By devising efficient assembly lines, Ford was able to achieve low production costs and enabled the gasoline vehicle to compete aggressively with its electric counterpart. While an electric roadster was sold for $1,750 (about $39,000), a gasoline car was priced at $650 ($15,000) and its price fell each year to reach as low as $360 (about $7,200 today) in 1916.

By the 1920's, the United States road system was much more developed, connecting distant cities, and thus requiring longer-range vehicles. Electric cars were unsuitable for rural driving, requiring being recharged every 18 miles or so, through a process that took between two and three hours. Not only was it cumbersome, it became expensive as well. At a rate of $15 per recharge, the cost of operating the vehicle was roughly 83 cents per mile, compared to less than 2 cents per mile for gasoline cars. The discovery of large reserves of oil in Texas and California made gasoline affordable and gasoline cars cheaper to operate. Also, the invention of the electric starter by Charles Kettering in 1912 eliminated the need for the hand crank. Gasoline cars were now able to travel farther and faster and were easier and cheaper to operate than their electric counterpart. Batteries were just too expensive, bulky, and heavy (Sperling & Gordon 2009). By the third decade of the century, the electric vehicle industry had disappeared.

Many specialized applications emerged during the next couple of decades including electric forklifts, milk floats and golf carts. Meanwhile gasoline cars enjoyed a remarkable success (Figure 14).

Efforts in the electric vehicle industry were picked up in the late 1950's when Henney Coachworks and the National Union Electric Company, which produces the Exide batteries, formed a joint venture to develop a new electric car, the Henney Kilowatt. The car was produced in 36-Volt and 72-Volt configurations; the 72-Volt models had a top speed approaching 60 miles per hour and could travel for nearly an hour on a single charge. Despite its improved performance with respect to previous electric cars, it remained too expensive compared to equivalent gasoline cars, and production was terminated in 1961 with less than a hundred vehicles produced.

Electric concept cars were pursued in the years that followed, including the Scottish Aviation Scamp (1965), the Enfield 8000 (1966) and two electric versions of General Motors gasoline cars, the Electrovair (1966) and Electrovette (1976). Even a plug-in hybrid concept was proposed by General Motors in 1969. None of them however entered production. 1971 was an interesting year for the electric car, during which the Lunar Rover became the first manned vehicle to be driven on the moon. The vehicle was developed by Boeing and Delco Electronics.

The 1970's were turbulent times for the oil industry. With two massive energy crises and a volatile oil market, strong interest in more efficient transportation and alternative fuels was sparked. People began to experiment with hybrid vehicles. In 1974, Victor Wouk, known as the "Godfather of the Hybrid", retrofitted a 1972 Buick Skylark with a hybrid drivetrain for the 1970 Federal Clean Car Incentive Program. The concept, which was tested and proven to work, was rejected by the Environmental Protection Agency (HybridCars 2006). David Arthurs was yet another inventor who made a breakthrough in hybrid technology. The father of the regenerative braking system, he converted an Opel GT in 1978 into an impressive hybrid that exhibited a 75 miles per gallon fuel efficiency. In 1980, Briggs and Stratton developed "The Hybrid", a gasoline-electric hybrid automobile powered by a twin-cylinder on engine and a large lead-acid battery. Audi introduced an experimental plug-in hybrid in 1989, the Audi Duo, which could be operated either in gasoline or electric mode.

The 1990s saw numerous efforts being pursued by automakers to develop electric vehicles, driven by federal and state policies. The California Air Resource Board (CARB) initiated in 1990 a movement towards zero-emissions vehicles. Two percent of vehicles sold in the state of California were to be zero emitting by 1998, increasing to 10% in 2003. Chrysler proposed the TEVan, Ford the Ranger EV pickup truck, General Motors the EV1 and S10 EV pickup, Honda the EV Plus hatchback, Nissan the Altra EV miniwagon, and Toyota the RAV4 EV. General Motors introduced the notorious EV1 in 1996. The car was an all-electric two-seater, with a massive 1,175-pound lead-acid battery and a range of 70 miles. It was made available through limited and unusual lease-only agreements whereby the cars had to be returned to GM at the end of the lease period, with no option to purchase. By 1999, all cars were repossessed and destroyed by their manufacturer and a few were de-activated and donated to museums and engineering schools. Later on the Big Three sued CARB in Federal Court, leading ultimately to the withdrawal of the zero-emissions vehicle mandate. Efforts to develop electric vehicles were subsequently completely terminated.

The Partnership for a New Generation of Vehicles (PNGV) program, initiated by the Clinton administration in 1993, is considered to be responsible for the development of hybrid vehicles. A collaboration between Chrysler, Ford, General Motors, and the Department of Energy, the goal of the PNGV program was to develop vehicle prototypes with threefold improvement in fuel economy, or what amounted to an 80 miles per gallon car. The Big Three quickly agreed that diesel hybrids would be the technology of choice, and dawdled for the next few years.

Japanese makers, alarmed by the 1993 coup, quickly went to work. In 1997, Toyota launched the Prius, its own hybrid version, in Japan, followed by Honda who introduced the Insight in the Japanese and American markets in 1999. The Insight was the first hybrid to be sold in the U.S. after the Woods hybrid of 1917. Toyota followed suit the next year by introducing an improved version of its Prius in the U.S. market. While the Detroit automakers all had hybrid prototypes by early 2000 (Sperling & Gordon 2009), none entered production.

Hybrid technology, based on nickel metal hydride batteries, took some time to pick up in the American market, with fewer than 10,000 vehicles sold in 2000 (Figure 15). By 2003, that number had jumped to a little less than 50,000. Toyota followed up with a significantly enhanced upgrade in 2004, which eventually turned out to be a huge market success. Prius sales doubled that year to nearly 30,000 vehicles and almost doubled again in 2005 to reach 54,000 vehicles (U.S. DOE Vehicle Technologies Program 2010).

Later that decade, with oil prices reaching all-time highs, interest in electric vehicles was renewed. Tesla Motors introduced the Roadster in 2008, a two-seater with a 450kg battery pack and a range of 220 miles. This high-performance car was the first to use lithium-ion batteries, very similar to those used in laptops. Another pioneer in the industry is Chinese battery and carmaker BYD which launched the F3DM, the first mass-produced plug-in hybrid vehicle in the world, in 2008 and an all-electric sedan in 2009. Chevrolet will also be introducing the first plug-in hybrid vehicle to be produced and marketed in the U.S. by 2011. Fisker Automotive is also planning to roll out its own plug-in hybrid version, the Karma, which is expected to hit the market that same year.

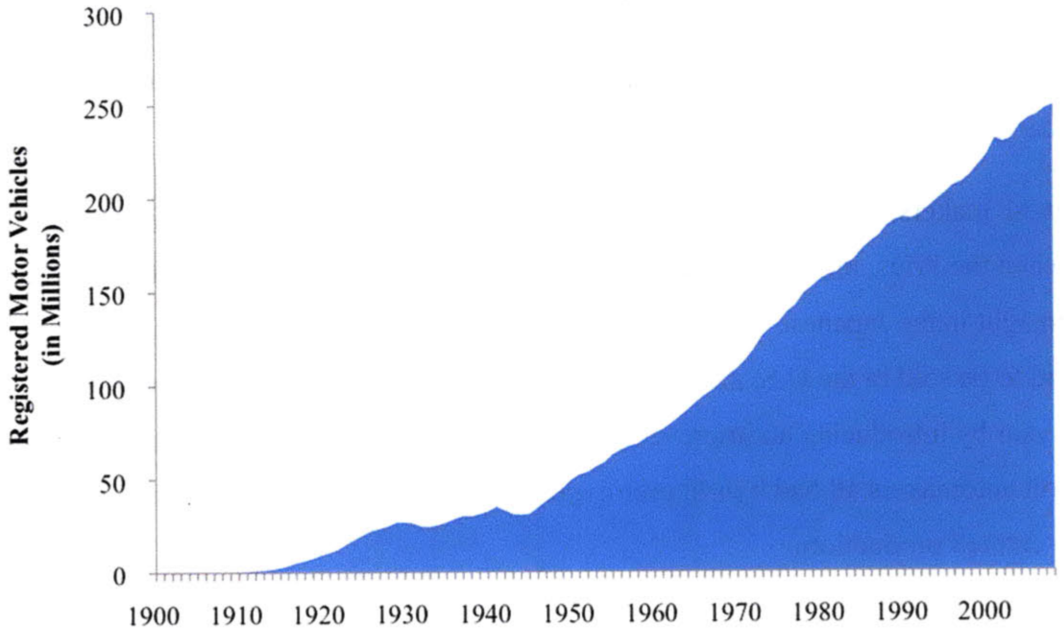


Figure 14: Registered Motor Vehicles in the United States, 1900 - 2008. Source: (U.S. Department of Transportation 2010)

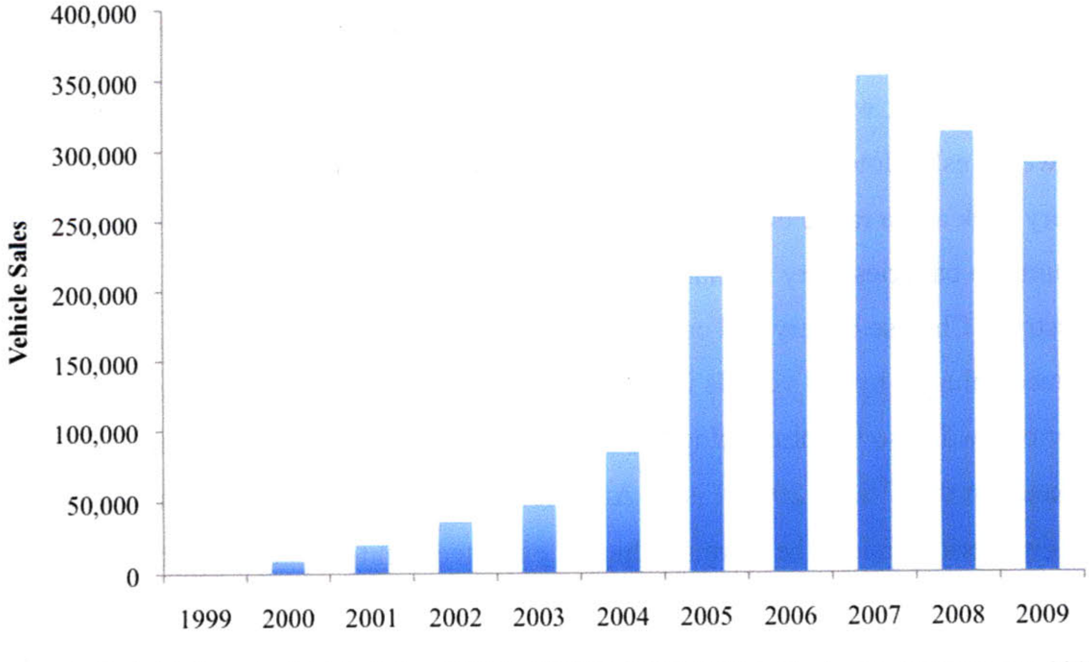


Figure 15: Hybrid Electric Vehicle Sales, 1999-2009 (U.S. DOE Vehicle Technologies Program 2010)

Types of Electric Vehicles

While all gasoline cars run on an internal combustion engine and a similar drive train, electric vehicles can be configured in many different ways, and are typically differentiated by the extent of their electrification.

In essence, all electric vehicles comprise an electric motor and a battery. However, the extent of electrification and the configuration of the propulsion system generate a wide range of models. Those are the mild hybrid, full hybrid, plug-in hybrid, and all-electric vehicle. All of the models listed above with the exception of the all-electric vehicle combine an internal combustion engine with an electric motor/generator.

The mild hybrid contains a small electric motor and battery that provide start-stop functionality, regenerative breaking and acceleration assistance. The full hybrid features a larger motor and battery providing similar functionalities as the mild hybrid in addition to enabling the car to run on pure electric energy at low speeds. A plug-in hybrid electric vehicle is essentially a full hybrid with a larger battery that can be charged with electricity from the grid. The bigger battery enables an extended driving range in pure electric mode, even at higher speeds. Once the battery is fully discharged, the vehicle can then either run on a smaller combustion engine like a regular conventional car or use the engine to charge the battery and extend the driving range. A fully electric vehicle relies solely on an electric drive train. Its performance tends to be limited by the size of its battery, which defines the maximum driving range.

Electric Vehicles and Battery Technology Limitations

The absence of lithium-ion-powered electric vehicles on roads and highways to date is due to a series of limitations involving mainly the battery component. Since lithium-ion batteries are a relatively nascent technology in the automotive industry, barriers need to be overcome in order to achieve a high-performing, safe and economical electric vehicle that can compete with gasoline-powered cars. Some of the major challenges that need to be addressed include cost, all-electric driving range, safety, electricity demand and charging infrastructure.

Cost

Cost is probably lithium-ion's Achilles heel when it comes to electric drivetrain applications. Even if all other challenges were addressed, with battery packs reaching a price tag of $1,000 to $1,200 per kWh or $18,000 for an all-electric car electric vehicles remain economically unviable compared to their gasoline-fired counterparts. Even hybrid vehicles powered with nickel metal hydride batteries, which are less costly than lithium-ion, remain more expensive than gasoline cars and have payback periods longer than three years.

While the prices of gasoline and electricity affect the economics of electric vehicles, the cost of batteries needs to be drastically reduced before they are seriously considered for mass deployment. The United States Advanced Battery Consortium has set a cost target of $250 per kWh. However, many analysts and industry experts see substantial challenges in achieving this goal by 2020 (Boston Consulting Group 2009a). When looking at the major cost drivers (Figure 17), the cathode active materials and purchased parts account for nearly half of battery costs. Given that most manufacturers employ automated processes, labor has a minimal share of total cost (R. J Brodd 2005) and thus manufacturing location is inconsequential (Boston Consulting Group 2009a). That notion has been discredited however when Chinese battery maker BYD introduced cheap labor instead of costly machinery and succeeded in reducing costs. Detailed cost modeling performed by Argonne National Laboratory indicates that in high production volume (greater than 100,000 packs per year), the costs to the OEMs can be reduced by up to 50% (Burke & Kamath 2009).

All-electric Driving Range

As described earlier, energy density translates directly to driving range. Most all-electric vehicles that will enter the market in the near future have ranges between 100 and 200 miles for a single charge. Naturally, the bigger the range, the heavier and the more expensive the battery becomes. On the lower end, the Nissan Leaf has a range of a 100 miles with a battery pack estimated to cost $12,000. On the other end of the spectrum, the Tesla Roadster has a range of 200 miles with a battery pack that is estimated to cost around $30,000. While this range is sufficient for the majority of vehicle trips, consumers still react negatively to a limitation in driving range especially given that the alternative internal combustion engine has much fewer limitations in that regard.

Safety and Abuse Tolerance

Batteries for electric vehicles may cause safety hazards for many reasons. Due to their high power ratings, batteries tend to overheat, especially in the case of overcharging and discharging at very high rates. Defects in manufacturing are likely to produce unstable cells that could potentially hold short-circuits. These factors either cause or increase the likelihood of thermal runaway, which triggers intense heat generation that may lead to a fire or explosion.

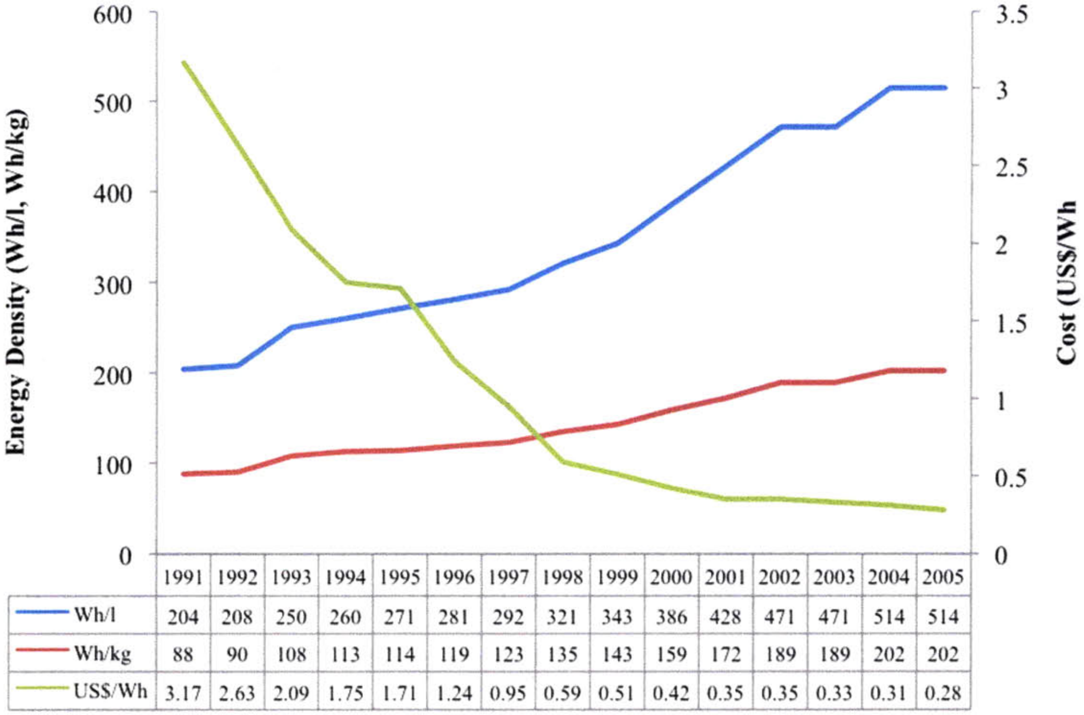
Current efforts to address these issues involve installing a battery management system (BMS), which ensures appropriate thermal cooling and monitors voltage variation. While acceptable safety is achieved, these systems tend to raise the price tag of the battery pack, which is already deemed to be too expensive. Abuse tolerance is also of great concern given that cars are prone to accidents and crashes. Batteries need to be able to withstand the forces and strains that result from such impacts without compromising the inner components and electrifying the whole vehicle body.

While the success of electric vehicles largely hinges on the development of powerful and sturdy yet low-cost batteries, electricity supply and distribution is as important. As such, other challenges that are extrinsic to the battery and car itself also arise as electric vehicles are deployed at large scale. These include electricity demand and charging infrastructure.

Electricity Demand

How to charge millions of electric vehicle batteries every day? A population of electric vehicles of that magnitude will create a significant increase in electricity demand that will cause a strain on the grid.

Utilities and electricity service providers have yet to devise a solid system which allows the “frail” grid to support a large number of batteries being charged. Utilities have a tremendous challenge ahead of them especially with the integration of renewable sources into the grid.



	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Wh/l	204	208	250	260	271	281	292	321	343	386	428	471	471	514	514
Wh/kg	88	90	108	113	114	119	123	135	143	159	172	189	189	202	202
US$/Wh	3.17	2.63	2.09	1.75	1.71	1.24	0.95	0.59	0.51	0.42	0.35	0.35	0.33	0.31	0.28

Figure 16: Lithium-ion Battery Learning Curve for Energy Density and Cost. Source: (Battery University 2004)

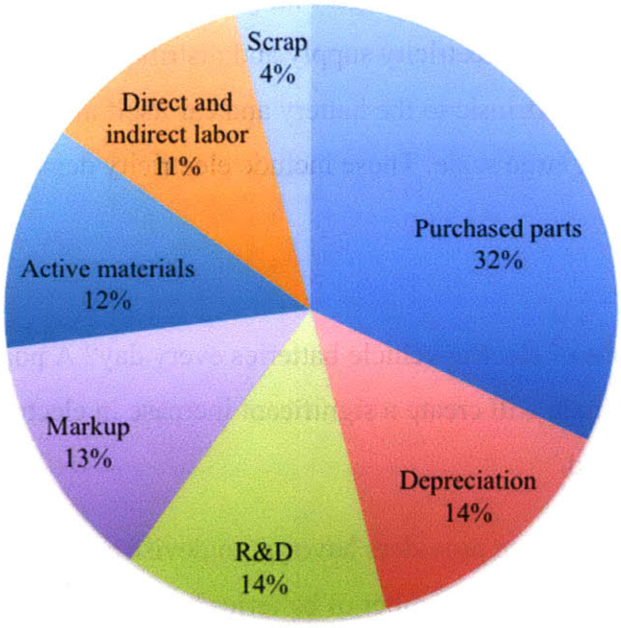


Figure 17: Battery Pack Cost to OEM at Low Volumes. Source: (Boston Consulting Group 2009a)

Not only will they have to manage an intermittent and non-dispatchable supply of electricity, they will also have to meet an ever-increasing and unpredictable demand. Smart grid technologies and other innovative approaches to manage the grid will be required to address burgeoning demand and alleviate additional supply requirements. With the right technology and planning, battery charging could possibly be the solution for balancing the grid and leveraging renewable energy sources. In fact, a novel concept has emerged lately called "Vehicle-to-Grid", whereby electric vehicle batteries are used as energy storage units to support the grid. When these vehicles are not on the road, their batteries can serve as a backup unit to deliver power whenever needed. Such concepts could possibly improve the economic viability of electric vehicles by creating value based on reserve power needs. However, many issues need to be addressed. Vehicle-to-Grid applications will inevitably accelerate the degradation of the battery due to more frequent charging and discharging. Moreover, tying the car to the grid limits its owner's mobility given that the effective driving range would be reduced if a portion of the stored energy were discharged into the grid. All of these issues will need to be addressed before Vehicle-to-Grid applications are implemented.

Charging Infrastructure

Electric vehicles requiring charging such as plug-in hybrids and all-electric vehicles typically use conventional power outlets or dedicated charging stations that require hours before reaching a full charge. It is anticipated that most people are likely to charge their electric vehicles overnight, as they do with their mobile phone. This provides more than sufficient time to reach a full charge, and the cost of electricity is likely to be cheaper as demand is lower. Other likely sites for battery charging stations include the workplace, shopping malls, stores, restaurants, etc. Additional stations must also be installed along connecting highways to provide electricity for cars travelling long distances. In these cases, hours of charging are not really feasible and other options must be devised. Fast charging is one possible solution to that problem, whereby the time required to charge the battery is significantly reduced by forcing more power at a faster rate into it. This option also has disadvantages. Fast charging tends to cause the battery to overheat and thus might comprise its performance and lifespan.

Nissan has already taken active measures to develop a public charging infrastructure, by partnering with many local governments and private companies. Charging companies have also burgeoned in recent years. Coulomb Technologies, founded in 2007, has already sold more than 2,000 charging stations and is taking orders from major American and European cities. ECOtality is another company developing charging technologies and services, with plans to be among the first to expand in China, one of the most promising electric vehicle markets in the world. Other companies like Project Better Place have opted for a more radical solution than simple charging stations which relies on swapping the entire battery. Hours of charging can be substituted by a handful of minutes, similar to the time spent at a gas station. Clearly, such concepts also require an infrastructure of their own, involving a network of battery swapping stations, and have a series of other challenges. For instance, all battery packs need to be standardized across platforms, models and manufacturers. Swapping also entails the presence of many more battery packs in the system, raising capital intensity significantly.

Electric vehicles clearly have a series of challenges that need to be overcome before enabling deployment at large scale. Perhaps the most critical factor in the equation is the battery component, where cost remains the major showstopper. The lithium-ion battery industry has made significant progress since its inception, driven primarily by the electronics industry, to a point where the technology is sound enough to be used in electric drivetrain applications. The next section aims to recount the historical evolution of the lithium-ion battery industry in an aim to capture the factors that accelerated the progress and development of the technology.

Section 3 – The Evolution of the Lithium-Ion Battery Industry

Since its emergence in the 1990's, lithium-ion battery technology has revolutionized our way of life by enabling a wide array of handheld electronic devices such as mobile phones and laptop computers and even iPods and iPads. The technology has witnessed a tremendous evolution, one where performance increased and cost decreased rapidly in just two decades, with further improvements expected. Illuminating this history provides lessons on how innovation is born, how it is cultivated and developed and, possibly, how it is preserved and sustained.

But before recounting this history, it is important to understand how the industry is organized and how players are positioned along its value chain.

The Organization of the Lithium-Ion Battery Industry

Transforming raw materials to a high performing battery pack involves a series of complex and intricate yet well-defined processes. The value chain of lithium-ion batteries for electric vehicles consists of five distinct stages: component production, cell production, module assembly, pack assembly, and vehicle integration.

The first stage of the value chain is to produce the anode and cathode active materials, binder, electrolyte and separator. To a large extent, the chemistries involved in the active materials of the anode and cathode are typically what differentiate various lithium-ion battery technologies. Their production therefore characterizes a manufacturer's competitive advantage and is considered as part of his core competency. Binders, electrolytes and separators are often purchased from external vendors. Despite the differences in their impact on battery performance, battery chemistries typically have similar manufacturing processes. The anode and cathode active materials are used to form the electrodes, which act as the current conductor in or out of the cell. The electrodes are formed by coating the active materials on both sides of a metallic foil. The anode active material is typically a form of carbon graphite and the cathode is a lithium metal oxide. Copper is usually used for the anode and aluminum for the cathode. The active materials are typically delivered in the form of black powder and the metallic foils are delivered in the form of large reels. The first stage involves mixing the active material with a conductive binder to form a slurry, which is then spread on the surface of the metallic foil. The metallic foils, which are directly mounted on the coating machines, are unreeled through precision rollers as the slurry is applied on their surface. A sharp knife located just above the foil controls the thickness of the electrode coating. The coated foils are then fed into a drying oven to bake the electrode material onto the foil. Once baked, the coated foils are then processed into slitting machines to cut the foil into narrower strips according to the desired electrode size. To avoid any contamination which could undermine the performance of the battery, processing of the anode and cathode are generally performed in separate rooms.

The second step of the value chain is cell assembly. There are two basic cell designs, depending on how the electrodes are packed, and which cell casing is used. Cylindrical cells contain spirally wound electrodes inserted in a cylindrical container, while laminate cells use stacked electrodes in a rectangular casing (Figure 19). Cylindrical cells allow for large electrode surfaces, which enable a higher current carrying capacity. Laminate cells are typically used for battery applications requiring high-energy capacities given their optimal use of space. They allow the use of multiple electrodes in a single cell, but also require a more intricate manufacturing process, which ultimately increases the cost. Despite the variety in cell design, manufacturing processes are generally the same. Any differences will be highlighted in the subsequent description.

The first stage in the cell assembly is to build the electrode sub-assembly, in which the separator is inserted between the anode and cathode. In the case of a cylindrical case, the anode and cathode foils divided by the separator are wound onto a cylindrical mandrel to form a roll. For the laminate form, the anode and cathode foils are stacked alternately and kept apart by the separator. The presence of multiple electrodes requires a clamping mechanism that connects all the anodes together and a similar one to connect all the cathodes. This additional process drives the complexity and labor requirements of manufacturing and thus the cost. The terminals of the electrodes are then connected together with a safety device before being inserted into the cell case. The case is sealed either through laser welding or heat processing, depending on the material, and a small opening is left to inject the electrolyte.

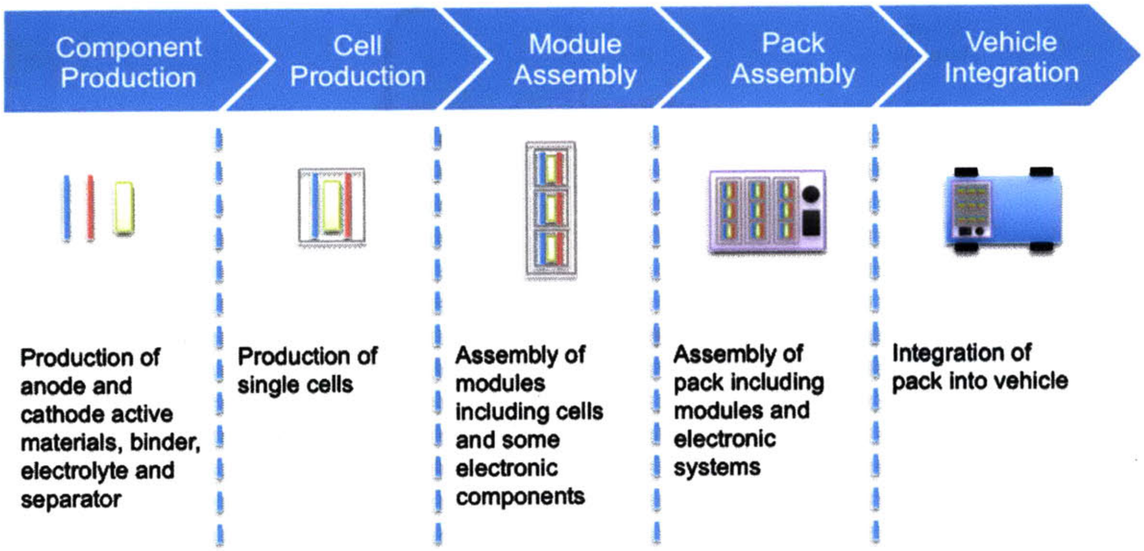
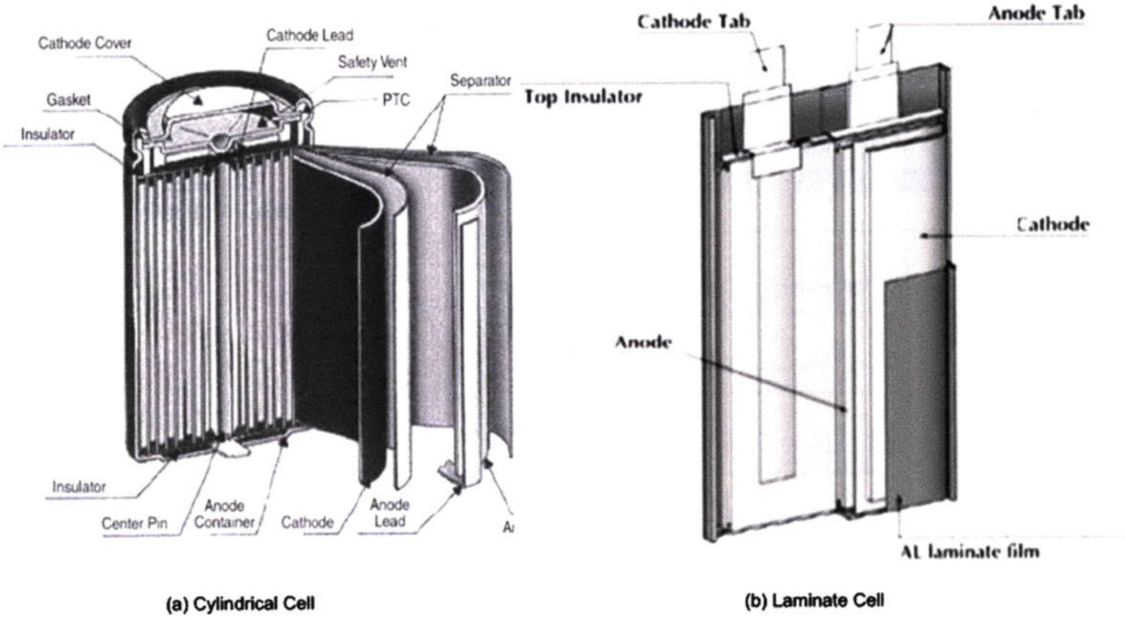


Figure 18: The Value Chain of Lithium Ion Batteries for Electric Vehicles (Boston Consulting Group 2009a)



(a) Cylindrical Cell

(b) Laminate Cell

Figure 19: Lithium-Ion (a) Cylindrical and (b) Laminate Cell Designs. Source: (Kiehne 2003)

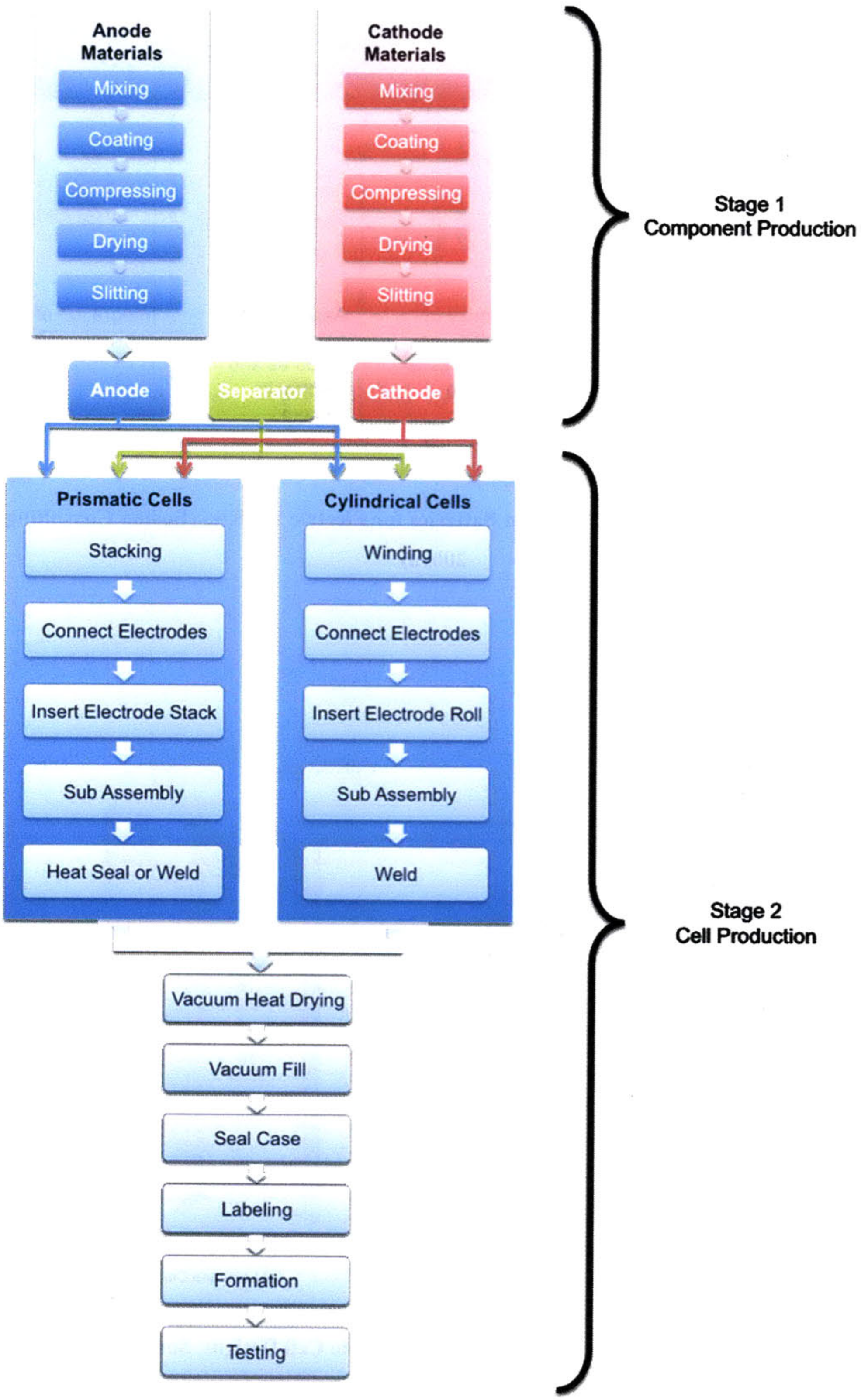


Figure 20: Stage 1 (Component Production) and Stage 2 (Cell Production) in the Lithium-Ion Battery Value Chain

The electrolyte insertion is performed in a dry room. Any moisture could react with the electrolyte and lead to its decomposition and the emission of toxic gases. Once the cell is sealed and labeled, it goes through at least one precisely controlled charge/discharge cycle – called the "formation process" – to activate the working materials. The cells then go through a rigorous quality control before being sold or transferred for module assembly. While cell assembly processes have become highly automated, some factories, especially smaller manufacturers in East Asia, still use manual assembly methods.

In the third step, cells are grouped into modules with electronic components. Because lithium-ion cells are subject to severe damage when overcharged or overdischarged, a control/safety circuit is included in each module. The circuit generally consists of a monitoring PCB (Printed Circuit Board) with its own microprocessor that communicates the voltage and temperature of its module to the rest of the vehicle (Berdichevsky et al. 2006).

The fourth and final step of the battery manufacturing process involves building the battery pack by assembling several modules together and adding an electronic control system to manage power, charging and temperature for additional safety. The pack is also fitted with a thermal management unit that circulates a fluid (air or liquid) keeping the cells thermally balanced. In addition to enhancing the safety of the overall system, the unit extends the life of the battery pack (Berdichevsky et al. 2006). It is usually up to the car manufacturer to design the battery pack according to its specific requirements to ensure proper vehicle integration.

Finally, once the battery pack is assembled, it needs to be integrated into the vehicle structure through connectors, plugs, mounts, etc. This step is naturally carried out by the auto manufacturer, who needs to ensure that the battery pack is well integrated into the vehicle drive train. The use of electronics and software ensures the proper communication between the battery pack and the rest of the system. Figure 18 summarizes the five stages of the value chain.

Historical Development of the Industry

The lithium-ion battery industry has had quite an interesting history. While the initial pathbreaking work took place in Europe and the United States, Japanese companies succeeded in acquiring the technology and developing it for Japan's consumer electronics industry. Manufacturing then spread throughout the Asia Pacific region, driven by government support and cost saving opportunities. With the rebirth of electric vehicles, the United States is investing heavily in an attempt to become a leader in manufacturing batteries for electric vehicles, while Japan, South Korea and China are repositioning themselves to capture the market for electric vehicles after having dominated the battery market for consumer electronics.

Birth in Europe and the United States

Pioneering work on the lithium battery began as early as 1912 by G. N. Lewis, but it was not until the 1970's that the first non-rechargeable lithium battery was proposed by M. Stanley Whittingham at Exxon, the American energy giant. Whittingham used titanium sulfide as the cathode and pure lithium metal as the anode (Whittingham 1976). Batteries in which the anode is made from metallic lithium could explode, and posed serious safety issues. As a result, a new approach was introduced in which the anode, like the cathode, was made of a material containing lithium ions. Discharging and recharging the battery was then simply enabled by the transport of lithium ions between the two electrodes, back and forth. This phenomenon, which later became known as the "rocking-chair" technology, enhanced the safety features of batteries and made them much more stable. This is also probably why they are known as "lithium-ion" batteries. In 1981, Bell Labs developed a workable graphite anode as an alternative to lithium metal, which allowed extensive cycling without significant loss of capacity (Basu 1981).

During that time, John Goodenough, an American physicist who is perhaps one of the most influential figures in the industry, proposed a pathbreaking cathode material. After completing his undergraduate studies at Yale University and his doctorate at the University of Chicago in 1952, Goodenough spent his early career at MIT's Lincoln Laboratories working on magnetic memory. He then moved during the late 1970's to head the Inorganic Chemistry Laboratory at Oxford University, where he identified and developed lithium cobalt oxide as a cathode material of choice for lithium-ion rechargeable batteries. Sony, the Japanese leader in consumer electronics, later adopted his technology to commercialize the first lithium-ion batteries in 1991. In 1983, along with Michael Thackeray and other colleagues, Goodenough identified manganese spinel as yet another cathode material (Thackeray et al. 1983). Spinel showed great promise thanks to its low cost, good electronic and lithium-ion conductivity, and structural stability. Manganese spinel is still currently used in some commercial cells. In 1986, Goodenough joined the faculty of the University of Texas at Austin where he pursued his research on lithium-ion battery technology. In 1989, his work with Arumugam Manthiram showed that cathodes containing poly-anions, such as sulfates, produce higher voltage than oxides due to their inductive effect (Manthiram & J.B. Goodenough 1989). Goodenough is undoubtedly one of the major contributors to lithium-ion battery technology. He was later awarded the prestigious Japan Prize in 2001 for his discoveries of the materials critical to the development of lithium-ion batteries. And in 2009, U.S. Energy Secretary Steven Chu awarded Goodenough the Enrico Fermi Award, one of the oldest and most prestigious awards given by the U.S. Government, for his invaluable contributions to the lithium-ion battery industry. Notably, in 2002 Goodenough reported to the Economist that battery firms in the West rejected his methods (The Economist 2002).

Adoption and Development in Japan

Early work on lithium batteries started in Japan in the 1980's. Building on the work of Basu (Basu 1981), Goodenough (Manthiram & J.B. Goodenough 1989; Thackeray et al. 1983) and others, Asahi Kasei Co. conceived and developed the lithium-ion battery as it is known today by proposing a substitute anode based on carbon (Yoshio et al. 2009). Sony later announced production in 1990 and introduced the first commercial lithium-ion cells to the market in late 1991 (R. J Brodd 2005), followed in 1992 by A&T Battery Co., a joint company between Toshiba Battery and Asahi Kasei Co. The technology was to a large extent based on the work of Goodenough in the West.

From then on, Sony and other Japanese vertically integrated electronics companies including Matsushita and Sanyo carried on research and development efforts in the industry. Sony, founded in 1946, had succeeded in commercializing the first transistor radio in 1955 after obtaining the license to transistor technology from Bell Labs in the United States. In 1975, Sony entered a joint battery-manufacturing venture with U.S.-based Union Carbide Corp. to form Sony-Eveready. The agreement stated that Union Carbide Corp. was to develop the batteries and Sony was to manufacture and market them in Japan. Sony's ultimate goal was to develop rechargeable batteries to replace its dry cell battery technology, which caused environmental mercury contamination. Lithium technology had great promise at that time. In 1986, Union Carbide announced that it would sell its entire consumer goods business to cover compensation payments after an explosion at one of its plants in Bhopal, India. After a series of negotiations, Sony bought Union Carbide's share of Sony-Eveready and reestablished its battery business under Sony-Energytec Inc. The company then initiated in 1987 a project to develop rechargeable lithium batteries. Multiple research efforts were pursued simultaneously, until the winning formula was discovered; an ionic lithium alloy called lithium cobalt oxide was used for the cathode and a carbon material for the anode. The battery was superior to its nickel metal hydride predecessor in almost every aspect. The product dubbed "lithium-ion rechargeable battery" was finally announced in 1990. Production facilities with the capacity to manufacture 100,000 units per month were already prepped for manufacturing and mass production was launched in 1991. After receiving favorable reviews for their batteries in one of their video recording devices – the Sony CCD-TR1 8 mm camcorder – other battery manufacturers decided to develop and produce lithium-ion batteries.

Matsushita Electric Industrial Co., better known as Panasonic Corporation, is one of the largest Japanese electronics manufacturers. It had started developing batteries as early as the 1920's and had been pursuing rechargeable battery technologies since the 1980's. In 1994, it became the third Japanese company to develop and manufacture lithium-ion batteries and soon positioned itself as a major supplier of lithium-ion batteries for electronics in the 1990's and 2000's (Figure 22).

Sanyo Electric Co. had a very similar story. Founded in 1950 by Konosuke Matsushita's (founder of Matsushita Electric Industrial Co.) brother-in-law and former Matsushita employee, the company's first product was a bicycle generator lamp. Soon after it expanded its product line and introduced the first plastic radio in Japan in 1952. The company went on to become a major player in electronic devices. After having introduced rechargeable nickel metal hydride batteries in 1990, it began marketing lithium-ion batteries in 1994 and became one of the largest global suppliers of lithium-ion cells (Figure 22).

Having moved rapidly through the development and commercialization processes of lithium-ion cells, these Japanese firms succeeded in capturing a large portion of the market early on. The new technology was quickly adopted for portable electronic devices such as camcorders, CD players, compact televisions sets, word processors, portable computers, mobile cellular phones, and others. Lithium-ion battery technology became an attractive selling point in electronic products and soon substituted for its predecessors such as nickel-cadmium and nickel metal hydride thanks to the smaller volume, lighter weight and overall better performance of the new technology. Given the nature of Japanese electronics companies, battery suppliers tended to be vertically integrated given that proximity to the device designer provides significant advantage in developing new products for the market (R. J Brodd 2005).

Meanwhile, U.S. companies attempted to enter the market with no success. Duracell and Eveready (now Energizer Holdings), two major U.S. battery companies, initiated research and development efforts in 1992 with the intent of ultimately manufacturing lithium-ion batteries in the U.S. (R. J Brodd 2005). Energizer had even built a manufacturing facility in Gainesville, Florida with state-of-the-art equipment in 1997 and planned to start production in 1999-2000. Right before production started, however, the price of lithium-ion cells decreased sharply. When the company reassessed the profitability of its investment, it realized that it could actually buy cells from Japan at a lower price than its manufacturing costs (R. J Brodd 2005). The decision to exit the industry was obvious, and soon after, Duracell followed suit.

Patents	**Patent No.**	**Application Date**	**Name**	**Company**
Transition metal oxides as cathode, $LiCoO_2$	US 4,302,518	1980/3/31	J.B. Goodenough	United Kingdom Atomic Energy Authority
Graphite/Li in molten salt	US 4,304,825	1980/11/21	S. Basu	Bell Telephone Laboratories, Inc.
Graphite/Li in nonaqueous solvents	Japan 1769661	1981/6/18	H. Ikeda, K. Naruwaka, H. Nakashima	Sanyo
Graphite/Li in nonaqueous solvents	US 4,423,125	1982/9/13	S. Basu	Bell Telephone Laboratories, Inc.
Li-Ion battery (battery based on carbonaus material)	Japan 1989293	1985/5/10	A. Yoshino, K. Jitsuschika, T. Nakajima	Asahi Chemical Ind.
Carbonous/Li nonaqueous	US 4,959,281	1989/8/29	N. Nishi	Sony Co.
Graphitized mesophase carbon	Japan 2,943,287	1990/9	Kawagoe, Ogino	Bridgestone
Additives for Gr vinylene carbonate	Japan 3059832	1992/7/27	M. Fujimoto, M, Takahashi, A. Nishio	Sanyo
Additives for Gr vinylene carbonate	US 5,626,981	1997/6/5	A. Simon, J-P. Boeuve	Saft
Additives of propane sulton	US 6,033,809	1997/8/22	S. Hamamoto, A. Hidaka, K. Abe	Ube

Table 3: Important Patents in Lithium-Ion Battery Technologies (Yoshio et al. 2009)

Deployment of Manufacturing in East Asia

From the early 1990's, there was very strong support in Japan, Taiwan, Korea, China and other countries in Southeast Asia by both government and industry for investment in competitive efforts to capture global market share in the battery industry (R. J Brodd 2005). Many companies sought to move their operations to Southeast Asia, to take advantage of lower labor costs, especially given that some of the later-stage manufacturing processes were quite labor-intensive at that time.

The industry first began to shift from Japan to China where some major producers sought to take advantage of low-cost loans and production facilities provided or supported by Chinese government policies (R. J Brodd 2005).

BYD Co. of China was founded in 1995 to manufacture rechargeable batteries and compete in the Chinese market against Japanese imports (Gunther 2009). Its founder, Wang Chuanfu, a chemist and government researcher, borrowed $300,000 from his relatives and rented about 2,000 square meters of space to produce batteries for mobile phones. Starting with two-dozen engineers, the company acquired its early technological expertise by studying patents owned by Japanese companies Sanyo and Sony, who later brought IP lawsuits against BYD. Within a few years, the company was selling batteries to companies like Motorola Inc., Nokia Corp., and Samsung Electronics Co. By 2000, it had become one of the world's largest manufacturers of mobile phones\ batteries. After going public on the Hong Kong stock exchange in 2002, the company witnessed fast growth, with business doubling each year. By 2005 it had captured more than half the world's mobile-phone battery market (Fishman 2005) and was the largest Chinese manufacturer (and in the top four worldwide) of all types of rechargeable batteries (Gunther 2009). By 2009, the company occupied 10% of global market share for lithium-ion batteries (Figure 22) and was the second largest lithium-ion battery supplier for mobile phones in the world (Shirouzu 2009). A main competitive advantage of the company is its low cost structure. This was achieved by replacing millions of dollars worth of machinery with cheap local labor (Fishman 2005). Batteries which are typically produced using highly-automated processes, are manually assembled in BYD's plants, where rows of workers, mostly women in their late teens and early 20's dressed in blue uniform assemble the components by hand (Shirouzu 2009).

Tianjin Lishen Battery Co. was another Chinese manufacturer to enter the lithium-ion battery industry. Founded in 1997, the company sought a different approach by implementing fully automatic processes and importing all of its equipment from Japan. It first targeted the mobile phones battery market, forging a strategic partnership with Motorola in 2000 and Philips in 2003. By 2005, the company had become one of the largest lithium-ion battery manufacturers in China.

BYD focused on minimizing cost by sacrificing quality. By relying on manual labor, production costs were reduced but waste rates reach up to 30% (Dongmei et al. 2010). Tianjin Lishen opted to automate its production line to ensure high quality. Both companies succeed in establishing themselves in the lithium-ion battery industry using entirely different business strategies.

South Korea followed China's footsteps by providing government incentives for what it believes to be a strategic technology (R. J Brodd 2005). Similarly to Japan, companies that sought to develop lithium-ion battery technologies were vertically integrated manufacturers of portable electronic devices such as Samsung and LG. They had pursued aggressive research and development efforts, making engineering improvements and developing new materials to enhance lithium-ion battery performance. Samsung, which began in the food business in 1938, entered the electronics industry in the late 1960's after having expanded into sectors as diverse as insurance, securities and retail. By the 1980's, Samsung had become a global leader in the electronics industry. This was largely due to the support of South Korea's president during the 1960's and 1970's, who banned foreign companies from entering the Korean market in order to protect Samsung from foreign competition and foster its electronics manufacturing business. The company shipped its first lithium-ion batteries in 1998 and soon after became one of the leading suppliers of lithium-ion cells in terms of performance and capacity (Figure 22).

Another company with a similar history is LG Chemical, the largest South Korean chemical company. Founded in 1947 – then Lak-Hui (pronounced "Lucky") Chemical

Industrial Corp. – it was the first Korean company to enter the plastics industry. As its business grew, it established GoldStar Co. (currently LG Electronics) as its electronics subsidiary and produced the first radio in South Korea in 1959. The company was renamed "LG" by combining "Lucky" from its plastics business and "Goldstar" from its electronics business. The company began research and development of lithium-ion batteries in 1995 and entered mass production in 1999 to become Korea's second biggest battery producer a few years later (Figure 22).

By 2003, BYD of China and South Korean companies Samsung and LG Chemical had become leading suppliers of lithium-ion batteries. During that time, Japanese companies maintained a solid lithium-ion battery manufacturing base led by Sony, Sanyo and Panasonic. In 2008, Panasonic announced that it would acquire rival Sanyo, the world's largest rechargeable battery maker. With its recent acquisition, which was completed in December of 2009, the company has more than 35% of the global market share of lithium-ion batteries (Figure 22) and aims to reach over 40% market share by 2016.

As of 2008, Japan, South Korea and China accounted for more than 95% of global lithium-ion cell manufacturing (Baylis 2009). Almost all of their production operations are located in Asia. Panasonic has plants in Japan and China. Sony has plants in Japan, China and Singapore. LG Chem has plants in South Korea, Japan, and China, and is currently building a plant in Michigan, U.S. to produce cells for General Motors. BYD on the other hand does all of its manufacturing in China.

It is also worth noting that most of the biggest Asian battery suppliers are vertically integrated producers of consumer electronics such as Sanyo/Panasonic, Samsung, Sony, BYD and LG Chem. They either started in the electronics industry and made their way to the battery business or started with the battery business and made their way to other electronic components.

In the meantime, small US companies and start-ups have continued to pursue innovative research and development with support from the Defense Advanced Research Projects Agency (DARPA) and other federal programs (R. J Brodd 2005). These new ventures have almost always only been successful in niche markets such as military and medical applications.

Quallion was one battery company that was created out of a need to power implantable medical devices. Alfred Mann was unable to find a battery supplier that produced a lithium-ion battery to power an injectable neuromuscular stimulator he was developing in the 1990's. The battery had stringent requirements including a minuscule size, a long shelf life and long cycle life among others. In 1998, he co-founded Quallion LLC with Hisashi Tsukamoto, who had more than 20 years of experience in developing various lithium battery technologies in Japan. Tsukamoto not only provided his expertise, he also brought in a team of Japanese experts in lithium-ion battery technology including material scientists, battery, manufacturing and process engineers and procurement specialists. Starting with only a handful of scientists in 1998, the company currently employs over 85 people. It designs and produces its cells in California, U.S. It has become a leading battery supplier for both internal and external medical devices thanks to technological leverage. The company also deals heavily with the military including the U.S. Air Force and the Missile Defense Agency as well as with NASA.

Polystor Corporation is one example of a U.S. company that was unable to compete against its Asian counterparts. Founded in 1993 as a spinout of the Lawrence Livermore National Laboratory, the company developed and manufactured lithium-ion batteries in small volumes for mobile devices and portable electronics. After a few years of research and development and a series of private and government grants, it entered production in 1996, by manufacturing its cell components in the U.S. and assembling them in South Korea (R. J Brodd 2005). At one point, the company achieved the highest capacity and energy density in the industry. However, after suffering a sharp decline in demand due to a global drop in mobile phones demand in 2001, it ceased operations in 2002.

Companies such as Polystor and Bolder Technologies were unable to fully commercialize their technologies due to insufficient funding for production facilities (R. J Brodd 2005). They could not deliver a commercial product within a time frame acceptable to venture capitalists. They never reached economies of scale and thus failed to compete with

Japanese and Chinese manufacturers who were engaged in a severe price competition to capture market share.

Current Industry Trends

The battery industry has been substantially energized by the recent surge of interest in electric vehicles. Merrill Lynch estimates that the lithium-ion battery market will reach $70 billion by 2020, while the Boston Consulting group projects that the market for electric-car batteries alone will reach $25 billion by then. Experienced Asian manufacturers are looking to sustain their market domination by capturing the battery market for electric vehicles. On the other hand, American companies are aggressively seeking to reestablish themselves as leaders in the lithium-ion battery industry, hoping to successfully skip two decades of development and manufacturing experience by relying on advancements in basic research and innovative technologies.

Revamping the Industry in East Asia

Japan, South Korea and China have dominated the lithium-ion battery industry for consumer electronics. With the launch of the electric vehicle industry, Asian companies are pouring billions into lithium research (Clayton 2009b) and capitalizing on their manufacturing expertise to maintain their edge. Not only have most Asian battery suppliers sought strategic partnerships with automotive manufacturers, Asian companies have gone as far as taking proactive approaches to secure strategic supplies of lithium, mainly in Latin America.

In Japan, Panasonic united with Toyota to form the joint venture Panasonic Electric Vehicle Energy Co, aiming to produce batteries for the electric vehicle industry. Toyota has been having trouble meeting demand for its popular Prius, mainly due to a lack of battery supply (Hybrid Cars 2009). In 2008, Panasonic invested more than $1 billion in a new factory that boosted its battery production capacity to about 300 million units a year by the middle of 2010 and plans to double that amount in a year and a half, targeting a wide range of applications from electric vehicles to backup power source and household energy storage systems. In 2009, the company acquired Sanyo, the largest producer of rechargeable batteries in the world, for $4.6 billion. The acquisition is expected to improve cost efficiency as a result of larger operating scales. Sanyo had spent over $500 million in 2008 for new production facilities. The company has provided hybrid vehicle batteries to Ford and Honda and it has also made sales deals with Toyota, Volkswagen AG and the Peugeot-Citroen group. Toyota has also made a strategic move in 2010 to secure strong position in the lithium-ion battery market. With the support of the Japanese government, a subsidiary and main supplier to Toyota Motor Corp. invested around $120 million to take a stake in a lithium-mining project in Argentina (Wakabayashi 2010). The move was the first of its kind to take place in the automotive industry. NEC, another Japanese battery manufacturer, partnered with Nissan to form the joint venture Automotive Energy Supply Corporation (AESC), which built a $115 million factory in Japan to supply lithium-ion batteries for the Nissan-Renault electric fleet. The joint venture also plans to market its batteries to potential customers in the automotive industry worldwide. Sony also plans to enter the battery business for electric vehicles, banking on the expertise it has gained in the electronics business. The company was already the first to develop lithium-ion battery modules for electric vehicles back in 1995. Despite its late re-entry, the company has announced in 2009 that it would commit more than $1 billion to develop and produce batteries for electric vehicles. So far, Japan has almost single-handedly dominated the battery market for electrified vehicles. Up until 2009, about 99% of the batteries that powered America's hybrid cars were made in Japan.

In China, looking to capitalize on its substantial battery production resources, BYD began expanding beyond its core competency, adding mobile phones and cars to its portfolio. Interest in automobiles was sparked in the late 1990's, when Wang, founder and CEO of BYD, quietly designated 20 engineers to scale up BYD's mobile phone-battery technology to power electric vehicles. The team managed to develop "The Flyer", an all-electric car that was just a step above a golf cart. However, the company's interest in automobiles was not revealed until many years later when it acquired a small Chinese automaker. After going public in 2002, the company acquired Tsinchuan Automobile Co., a Chinese state-owned car company to create BYD Auto a year later. The company was first assigned to develop a traditional gasoline car so that it could learn the basics of automotive design and manufacturing.

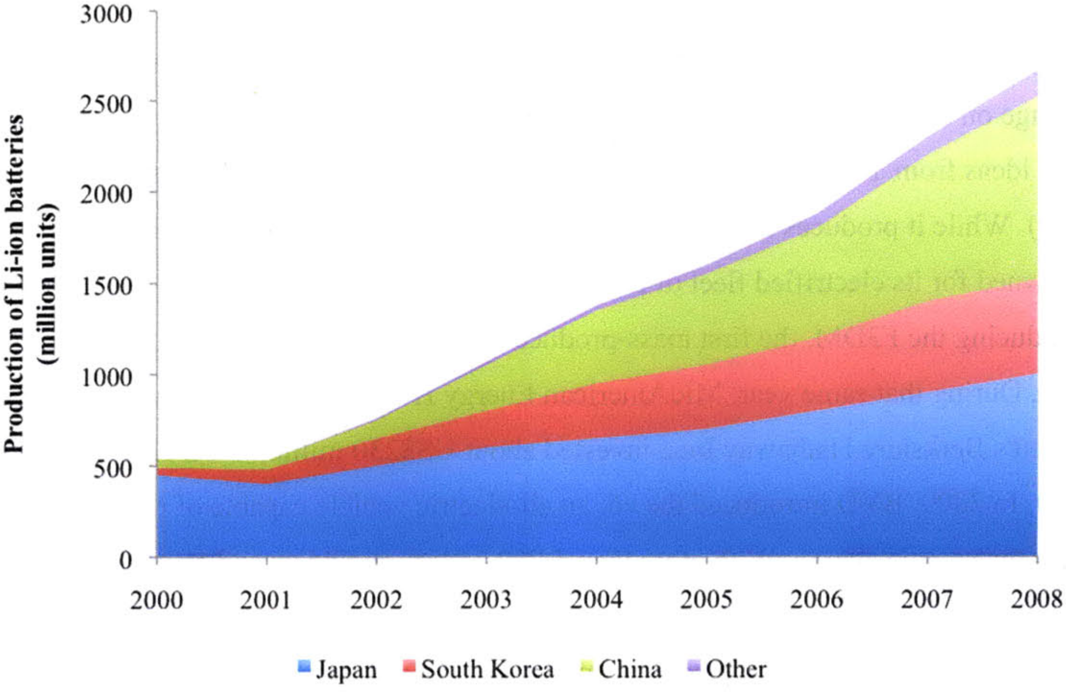


Figure 21: Global Production of Lithium-Ion Batteries By Country (Baylis 2009)

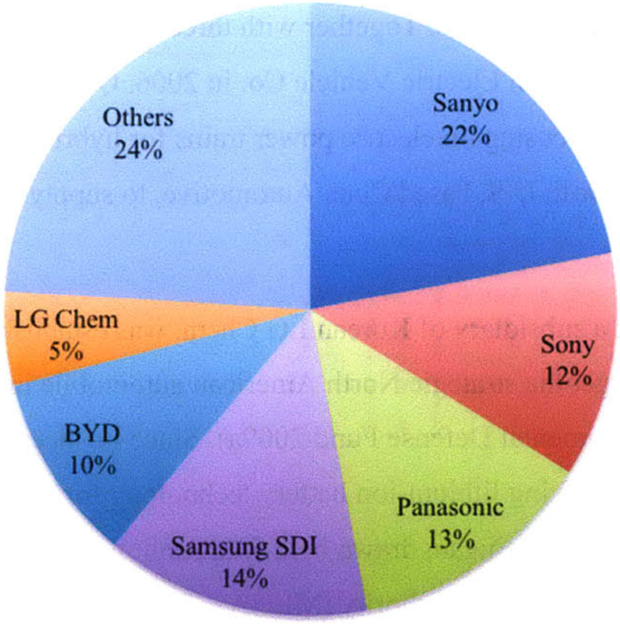


Figure 22: Global Market Share of Major Lithium-Ion Manufacturers, 2009. Source: (GBI Research 2010)

In 2005, BYD launched its first car, a small sedan called the F3, which was accused of being a copy of the Toyota Corolla. The company argued that it was "careful not to infringe on another company's intellectual property", but it admitted to "synthesizing good ideas from Toyota and others" and "benchmarking the industry's best" (Shirouzu 2009). While it produces and markets internal combustion vehicles, the company is more renowned for its electrified fleet of plug-in hybrid and electric vehicles. It succeeded in introducing the F3DM, the first mass-produced plug-in hybrid vehicle into the market in 2008. During that same year, MidAmerican Energy Holdings, a subsidiary of Warren Buffett's Berkshire Hathaway Inc., invested about US$230 million for a 9.89% share of BYD. In 2009, BYD introduced the e6, an all-electric vehicle capable of running 180 miles on a single charge. With more than 5,000 battery engineers and an equal number of auto engineers, the company has been growing at a rate of 100% for the past five to six years according to Li Lu, investor and advisor to BYD. Wang has declared that his company had the confidence to surpass GM and Toyota and other global automakers in electric-vehicle technology.

Tianjin Lishen Battery, the other major battery supplier in China, has also sought to take part in the electric vehicle business. Together with three other Chinese companies, it co-established Tianjin Qingyuan Electric Vehicle Co. in 2006. QYEV was aimed to develop clean energy vehicles, focusing on electric power trains for hybrid and electric vehicles. Lishen also partnered with U.S. based Coda Automotive, to supply batteries for its electric vehicle fleet.

Compact Power Inc., a subsidiary of Korean LG Chem, was established in 2001 in Colorado, U.S., to target the strategic North American automobile industry (Collaborative Economics for Environmental Defense Fund 2009a). Since its inception, it has focused on developing and modifying lithium-ion battery technology for vehicular use. In 2005, the company relocated to Michigan, drawn by a $3.8 million tax incentive proposed by the Michigan Economic Growth Authority (MEGA). The move also allowed CPI to get closer to the Detroit automotive hub. The facility houses the company's research and development activities and battery pack manufacturing. The company also received awards in 2006 and 2008 from the United States Advanced Battery Consortium

(USABC) to develop lithium ion polymer batteries for hybrid electric vehicles and plug-in hybrid electric vehicles. In 2008, the company managed to obtain a contract to supply lithium-ion batteries for General Motors' Chevy Volt. GM was also considering acquiring batteries from a partnership between Continental AG and A123Systems. CPI expects to set up a manufacturing/assembly operation in the U.S. by 2011, after having received a $151.4 million grant through the American Recovery and Reinvestment Act (ARRA) in 2009. LG Chem also has three research and development facilities located in China, Japan and South Korea, and three manufacturing facilities, two in South Korea and one in China, dedicated to the engineering and production of lithium-ion batteries.

As one of the few non-Japanese suppliers of nickel metal hydride batteries for electric vehicles, Samsung SDI has also sought to develop lithium-ion batteries for electric vehicles. After having partnered with Germany's Robert Bosch, it acquired U.S. battery producer Cobasys in 2009, hoping to tap into some of the company's hybrid car battery related technologies provided in some of GM's hybrid automobiles. The company also plans to start production of lithium-ion batteries specifically designed for electric vehicles in 2011.

Clearly, Asian manufacturers have strategically positioned themselves to capture the battery market for electric vehicles as the demand grows, betting on manufacturing expertise and low cost manufacturing.

Jumpstarting the Industry in the United States

In the U.S., many efforts are being pursued to jumpstart the rechargeable battery industry. Focusing mainly on lithium-ion technologies, U.S. companies are aiming to capture a portion of the battery market for electric vehicles, in the face of dominating Asian manufacturers. Modest research efforts persisted during the 1990's, and in the last decade many U.S. companies have emerged, building on research conducted in universities and national laboratories. The Obama administration has also identified the battery business as a strategic industry to decrease dependence on foreign oil and to stimulate the economy. It has awarded over $2 billion in stimulus grants to support national battery development and manufacturing.

As stated earlier, some research activity related to the lithium-ion battery industry persisted during the 1990's. In 1996, Goodenough and his coworkers identified lithium-iron-phosphate as a potential substitute for the cathode active material (Padhi et al. 1997). The discovery of the compound was considered to be a breakthrough since it enables the use of larger lithium-ion batteries that are suitable for automotive applications given their higher ratings in safety, stability and performance. Prof. Yet-Ming Chiang from the Massachusetts Institute of Technology built on the work of Goodenough and achieved better performance by using nano-particles of iron-phosphate.

Chiang's work led to the formation of A123Systems in 2001, based in Watertown, Massachusetts. The company successfully developed high-power lithium ion batteries, which were first commercialized in DeWalt's power tools in 2005. Its first deal in that industry allowed it to scale up to making millions of batteries, which helped lead to contracts for hybrid buses and also won the attention of automakers. A year later, the company received a development contract of $15 million from the United States Advanced Battery Consortium (USABC) to develop its battery technology for hybrid electric vehicle applications. In 2009, the company received a $249 million grant from the US Department of Energy Electric Drive Vehicle Battery and Component Manufacturing Initiative and $100 million in refundable tax credits from the Michigan Economic Development Corporation to build a lithium-ion battery manufacturing plant in Michigan. That same year, A123 went through an IPO, reaping $380 million on its first day. After adding in private investments and refundable tax credits, A123Systems is today a billion-dollar company. It was considered a legitimate contender to supply batteries for the Chevrolet Volt plug-in hybrid vehicle, but the company lost the contract to Compact Power Inc, a subsidiary of South Korean LG Chem. The loss of the contract was partly attributed to A123's inexperience at producing the kinds of volumes of batteries needed for automotive applications (Technology Review 2010). The company was still considered a startup according to GM vice chairman Bob Lutz, who stated that the automaker was more interested in flat laminate cells and LG Chem was regarded as a more established company with a more developed technology. A123Systems holds a contract to supply batteries for Th!nk's electric vehicles and maintains working relationships with several other car manufacturers including Chrysler, Daimler, BMW and General Motor. However, these relationships have yet to crystallize into actual contracts.

American firm Johnson Controls is also trying to break into the lithium-ion battery industry for electric vehicles. Established in 1885, the company grew to become a major supplier for automotive manufacturers. Its automotive business unit, called Automotive Experience, produces interior systems for light vehicles, including seating, overhead, doors, instrument panels, storage and electronics among others. In 1978 it acquired Globe-Union, a Wisconsin-based manufacturer of automotive batteries for both the replacement and original equipment markets, and in 2005, with its acquisition of Delphi's global automotive battery business, it became the largest producer of lead-acid automotive batteries in North America, with a 35% global market share and over 60% share in the U.S. (Lache et al. 2008). In 2006, the company announced a partnership with French battery company Saft to form the joint venture Johnson Controls-Saft Advanced Power Solutions (JCS). After having completed a lithium-ion battery development contract for hybrid electric vehicles with the United States Advanced Battery Consortium (USABC), the company received another contract worth $8.2 million to develop lithium-ion battery systems for plug-in hybrid electric vehicles. In 2009, the joint venture also received the single largest grant, worth $299.2 million, awarded by the United States Department of Energy under the American Recovery and Reinvestment Act (ARRA) to build domestic manufacturing capacity for advanced batteries for electric drive vehicles. During that same year the company was also awarded incentives totaling $168.5 million from the State of Michigan to establish a battery production facility in Michigan. The company currently produces lithium-ion cells in France under the joint venture and performs its battery assembly in Hanover, Germany and Milwaukee, Wisconsin. It plans to supply Ford, Mercedes, BMW, Chery and SAIC with batteries for their hybrid fleets.

EnerDel is an active player in the industry as well. Founded in 2004 through a joint venture between Ener1 and Delphi Corporation, the company aimed at developing and manufacturing compact, high performance lithium-ion batteries to power hybrid, plug-in hybrid and pure electric vehicles, based on technology originally conceived at the Argonne National Laboratory. The company also targets other applications including medical devices, military, aerospace, and electric utilities. Its manufacturing facility in Indiana is equipped with highly automated machinery enabling high throughputs. The plant was originally used by Delphi and General Motors, where they began developing battery technology for their first electric vehicle, the EV1 (Collaborative Economics for Environmental Defense Fund 2009b). The company produces its own anodes, cathodes and electrolyte using materials imported mostly from Asia (Blanco 2010). In 2007, the company was awarded a $6.5 million contract from the United States Advanced Battery Consortium to develop battery systems for hybrid electric vehicles. A year later, EnerDel became a wholly-owned subsidiary of Ener1. It announced in 2010 that it plans to expand its presence in Indiana by investing $237 million to build a third facility in the state, intending to meet anticipated demand for advanced battery systems for automotive and stationary applications. The expansion is supported by a $118.5 million grant awarded under the federal stimulus package and $69.9 million of state and local economic development incentives. EnerDel has established partnerships with Volvo, Th!nk, Nissan and Mazda, and is supplying batteries for a prototype hybrid version of the Humvee being tested by the U.S. Army (EnerDel 2010).

Valence Technology, founded in 1989 and headquartered in Austin, Texas, has also entered the battery industry for electric vehicles. Following research and development in the U.S., in 1999 the company set up its manufacturing operations in Northern Ireland after having received financial incentives from Invest Northern Ireland. The first chemistries it produced were lithium cobalt and lithium manganese, under a license for Bellcore's "flat cell" technology. In 2002, the company started producing batteries based on lithium iron magnesium phosphate technology. It moved its production to Suzhou, China in 2004 to take advantage of lower production costs. Since 2005, it has introduced three generations of battery modules for automotive applications. The company succeeded in penetrating the European market, building on strong government and public support. It has contracts with Smith Electric Vehicles, PVI, Oxygen SpA, Modec, and Wrightbus, all of which are European based companies offering electric transportation solutions. As of 2009, the company was one of the world's largest commercial suppliers of lithium iron phosphate batteries.

Other recent efforts have also been pursued to support the battery industry in the U.S. The National Alliance for Advanced Transportation Battery Cell Manufacture was formed in 2008 as an alliance between 14 members of the battery industry and Argonne National Laboratory to improve the competitiveness of the American battery industry and to expedite the development of advanced lithium ion battery technology. The alliance is modeled after SEMATECH, formed in 1987 by a group of U.S. semiconductor manufacturers with $1 billion in federal funding to build manufacturing plants and compete with Asian suppliers. The founding companies of the alliance are: 3M, Johnson Controls-Saft Advanced Power Solutions, ActaCell, All Cell Technologies, Altair Nanotechnologies Inc, Eagle Picher Industries Inc, EnerSys, Envia Systems, FMC Corp, MicroSun Technologies, Mobius Power, SiLyte, Superior Graphite, and Townsend Advanced Energy. Since its inception, the alliance has grown to more than 50 entities, including corporations, associations and research institutions. The alliance views the current market for rechargeable lithium ion batteries as too small for any one American company to build a plant on its own. It is therefore planning to build a single production facility where member companies would be able to purchase line time to build their own battery cells while keeping safe their proprietary information. A site in Hardin County, Kentucky was chosen to build a lithium-ion battery plant at a cost of more than $600 million.

Many U.S. battery companies emerged in the last decade. Some built on breakthroughs in basic research (e.g. A123Systems, EnerDel, Valence Technology), while others such as Johnson Controls-Saft were already well-established players in the lead-acid battery industry when they made their way into the lithium-ion battery industry. However, almost all American firms remain small players compared to the large Asian firms, which can claim decades of experience in the battery business for consumer electronics. While American firms in other areas of technology-based industry historically relied on basic research and technological innovations to lead their field, it is not clear whether this will be the case for the lithium-ion battery industry, especially given the Asian firms' substantial head start. After having completely dominated the global production of lithium-ion batteries, Asian firms are strategically repositioning themselves to capture the demand for batteries for electric vehicles when this arises, by offering suitable technologies at very competitive prices. Will the American underdogs be able to leapfrog into the lead? This remains to be seen, but the prospect for the American firms does not at this point seem very promising.

Section 4 – Interactions with Automotive Manufacturers Along the Battery Value Chain

The prospects for electrification of the automobile are growing. In the United States, American automakers are taking advantage of their recent financial troubles to restructure their product line and focus on green vehicle technologies. Japanese carmakers, having already led the hybridization of gasoline-powered vehicles, are seeking to maintain their edge by moving further up the electrification ladder. Chinese manufacturers, still lagging in meeting global quality standards, are hoping to leapfrog internal combustion technology by capitalizing on their expertise in battery manufacturing to develop electric vehicles. Mainstream European carmakers are also moving towards electric-powered vehicles to avoid falling behind.

The success of any company's endeavor in penetrating the electric vehicle industry hinges on the battery component in its vehicles. As discussed earlier, the battery will be the most critical component in the vehicle, dictating its cost, range and safety. As such, automakers will need to consider carefully issues of battery design, development and integration into their vehicles. The characteristics of the battery supply chain will affect the ability of the automobile manufacturers to achieve success in this domain, and the design of the supply chain is itself an important strategic variable.

While supply chain design for electric drivetrain purposes is a rather novel development in the industry, a significant amount of work has been dedicated to the study of the automobile industry's supply chain generally and its influence on the competitiveness of automakers.

Supply Chain Relations in the Automotive Industry

A modern passenger car contains more than 30,000 parts. Although original equipment manufacturers such as General Motors and Toyota assemble final vehicles, as much as 70% of the components typically come from external suppliers (Takeishi & Cusumano 1995). A clear trend in the auto industry has been towards increased levels of out-sourcing and heavier reliance on the supply chain as a source of competitive advantage

(Choi & Hartley 1996). In fact, a large share of control over quality, cost, and delivery has been transferred from OEMs to tier-one suppliers[7] (Florida & Kenney 1991) as they have assumed responsibilities for design and production of a larger number of components and subassemblies. This has been mainly driven by attempts by the OEMs to reduce the size of their supplier base and rely on fewer suppliers, with whom closer relationships have been established (Ballew & Schnorbus 1994; Bamford 1994). It is therefore critical for automakers to select and effectively build relationships with capable suppliers (Choi & Hartley 1996).

Historically, price competitiveness was the primary criterion on which contracts were awarded to suppliers, for both American and European automakers (Turnbull et al. 1992). The design effort often tended to be one-sided with either the automaker or supplier designing the component with little or no active collaboration between them. As pressures to further reduce costs were driven by competitive Japanese carmakers, buyer-supplier relations in the West came under increasing stress. OEM's demanded lower prices, sparking a price war among suppliers and leading to the bankruptcy and liquidation of many of them. These relations were equally damaging for automakers, which saw competitiveness in key areas such as quality, design and delivery decline. Japanese manufacturers had a different model. They typically had a more dedicated supplier base built on just-in-time supply, long term collaborative contracts, quality assurance, and they evolved a practice of "assembly-buying", whereby complete systems (e.g. braking systems, HVAC systems, electrical systems, etc.) are procured instead of individual components. Suppliers are heavily involved in product development, design, and technology transfer. Various studies have identified and described the supply chain practices that have played a major role in the international competitiveness of Japanese manufacturers (Abernathy et al. 1983; Cole & Yakushiji 1984; Cusumano 1985; Womack et al. 1990; Nishiguchi 1994).

As American and European OEMs learned and adopted Japanese practices (Helper 1991; Cusumano et al. 1991), suppliers earned more important roles and responsibilities, and

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[7] The automotive supplier base is broken into "tiers" according to the supplier status along the supply chain. Tier-one suppliers are those that supply the original equipment manufacturers (OEMs), or major automotive assembly firms, tier-two suppliers are those that supply to tier-one suppliers, etc.

longer-term supplier relationships became more common. Supplier selection has thus become of major importance. A survey performed by Cusumano and Takeishi (Cusumano et al. 1991) stated that design capability is one of the leading considerations in the selection of tier-one suppliers. Another statistical survey conducted by Choi and Hartley (Choi & Hartley 1996) confirmed this and went even further by affirming that the potential for cooperative, long-term relationships is crucial in supplier selection along the entire supply chain.

Supply chain relations in the auto industry have become even more elaborate as just-in-time and agile manufacturing practices have evolved. OEM's not only require the elimination of stockpiled component inventory from the assembly plant, but they also aim to produce multiple models, based on varying platforms, at the same manufacturing facility (Delaere 2002). This requires a great amount of synchronization between OEM's and suppliers to ensure efficiency along the supply chain.

Relationships between organizations in the supply chain can range from arm's length contracting to vertical integration, with a wide range of partnership arrangements in between (Lambert et al. 1996). Gereffi, Humphrey and Sturgeon go further in their analysis of supply chain governance to differentiate these intermediate relations into *modular*, *relational* and *captive* (Gereffi et al. 2005). In a *modular*-type relation, suppliers make products according to customers' specifications; however, they take full responsibility in developing and manufacturing these products. *Relational* supply chains rely on complex interactions between supplier and buyer, creating mutual dependence and high levels of asset specificity. In *captive* relations, smaller suppliers tend to be dominated by large customers, which exhibit a high level of monitoring and control.

Supply chain relations are particularly important given that the unit cost performance of most manufacturing operations is highly dependent on the effectiveness of purchasing (Turnbull et al. 1992). Bought-out items typically account for over 70% of the total cost of producing motor vehicles. This will also be true of electric vehicles, for which the battery costs could account for as much as half the cost of the total vehicle. Buyer-supplier relations therefore have a very significant impact on the efficiency and competiveness of automakers in the electric vehicle industry.

Methodology

A simple observation of the electric vehicle industry shows that many types of supply chain interactions exist between automakers and battery manufacturers. As such, a framework that classifies all these types of interactions needs to be established. Such a framework will allow a categorization of the various practices in the industry, which will facilitate their analysis. For the purpose of this analysis, a three-model framework has been identified[8]. The framework has then been validated with real observations of the industry layout, by fitting all of the interactions observed into one of the models identified.

Once the framework was identified and validated, a series of semi-structured interviews were conducted to shed light on some of the underlying mechanisms involved. Interview participants ranged from members of the automobile and battery industries, including executives and engineers, as well as academic researchers and consultants. The selection of the interviewees, especially in industry, was conducted in a way that allowed for all three types of interaction to be represented. The interviews revealed the automaker's point of view and/or the battery supplier's perspective for each model, providing key insights into how supply chains are viewed and organized. For instance, an OEM's motives to develop battery packs in-house rather than procuring them from an external supplier can only be known and understood through an interview or testimony. The interviews were conducted using a predetermined set of questions that covered all topics and issues of interest. However, interviewees were allowed to steer the conversation based on their own experiences and opinions.

The interviews were also complemented with personal observation and fact gathering from both industries to fill any gaps. Supplementary information was obtained from a review of literature and news articles, including print, broadcast and internet-based media.

An analysis of the three models was carried out, listing key industry players adopting them, and highlighting their advantages and disadvantages.

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[8] The three-model framework will be described in further detail in the following section.

In order to draw conclusions concerning the implications of these models for the competitiveness of the automakers, it was first necessary to consider the modularity[9] of the battery pack, since the complexity of the interactions between this component and the rest of the vehicle influences greatly supply chain relations. Insights into how the three models affect the competitiveness of automakers has been divided into short-term (10 years and less) and long-term (more than 10 years) implications.

Three Models of Interaction

Many types of supply chain relations between automakers and battery suppliers are observed (Figure 23). At one end of the spectrum, one automaker was previously a major lithium-ion cell manufacturer that decided to enter the automotive industry. The company thus today develops and manufactures the battery pack from scratch and integrates it into its vehicle lineup. At the other end of the spectrum, another automaker outsources the design and manufacture of its battery pack to an external supplier and merely assembles the final component into the vehicle. Between these two models there is a range of interaction types, where differentiation is based on the contribution of each automaker and battery supplier to the battery component. After a careful study of the industry, a three-model framework encompassing all of the interactions observed was identified.

In the first model, automakers develop and manufacture the battery pack in-house. Examples include Tesla Motors and General Motors, both of which acquire the cells from an external vendor, and BYD, which manufactures them in a vertically integrated organization. The second model involves automakers partnering or establishing a joint venture with a battery supplier. Those include automakers such as Toyota, Nissan and Mitsubishi. The third model is one where automakers have elected to acquire a battery pack already assembled by an external supplier and ready to be integrated into the vehicle. Companies to which this model is applicable include Daimler, BMW and Ford.

Vertical Integration: Developing Batteries In-house

In a vertically integrated organization, the product supply chain is typically integrated within the firm. This type of integration was widely popular in the early stages of the

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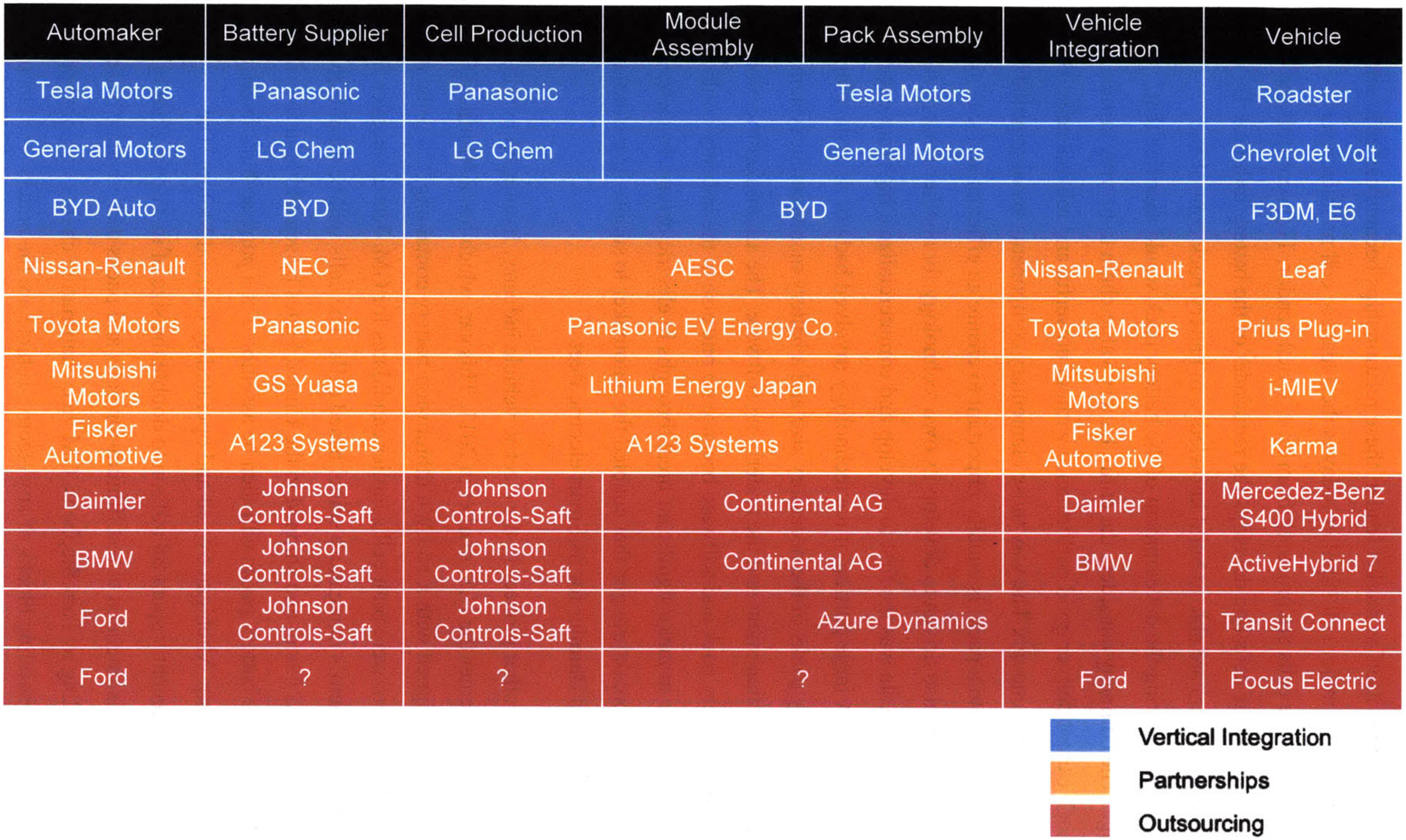
[9] A modular component is one that can be independently created and easily integrated into a system with simple interfaces.

automotive industry, before it adopted a gradual movement towards outsourcing. A similar structure is also observed in Asian electronics conglomerates. In the case of electric vehicles, this model pertains to automakers that design, develop and manufacture the battery packs in-house. For the purpose of this framework, cell manufacturing does not necessarily have to be integrated within the organization, as it requires a different set of knowledge in terms of development and manufacturing. While a fundamental understanding of cell behavior is important, knowledge of cell manufacturing is irrelevant to the production of battery packs. In this model, most automakers acquire cells from an external vendor (e.g., Tesla Motors, General Motors and Ford) while just a single automaker (BYD) manufactures its cells in a vertically integrated organization.

Tesla Motors is perhaps the first automaker to introduce a highway-capable all-electric vehicle. Founded in 2003, the company introduced its first vehicle, the Tesla Roadster, as early as 2006 and produced its 1000th car by January 2010. The Tesla Roadster is an all-electric sports car with a 236-mile range and an acceleration of 3.9 seconds from 0 to 60 miles per hour. The car is powered by a 53-kWh battery pack made of 11 modules each with an average of 618 cells. The modules are comprised of standard 18650 lithium cobalt cells, the chemistry that is typically used in laptop computers. Given its character as a startup, the company had no choice but to acquire its battery cells from an external supplier, as the alternative was too capital intensive. Tesla selects its cell supplier based on multiple factors, including performance, safety, and reliability, and these attributes are then confirmed by extensive internal and external testing. The company always seeks to use the best cells in the market and therefore developing close relationships with cell suppliers is very important. One of the biggest challenges the automaker faced at the outset was to establish such relationships with battery makers, given that electric vehicles were considered to be too dangerous and could potentially give a bad reputation to an already tarnished battery industry. The industry had already suffered from multiple incidents of laptop batteries exploding, causing millions of battery recalls.



Automaker	Battery Supplier	Cell Production	Module Assembly	Pack Assembly	Vehicle Integration	Vehicle
Tesla Motors	Panasonic	Panasonic	Tesla Motors			Roadster
General Motors	LG Chem	LG Chem	General Motors			Chevrolet Volt
BYD Auto	BYD	BYD				F3DM, E6
Nissan-Renault	NEC	AESC			Nissan-Renault	Leaf
Toyota Motors	Panasonic	Panasonic EV Energy Co.			Toyota Motors	Prius Plug-in
Mitsubishi Motors	GS Yuasa	Lithium Energy Japan			Mitsubishi Motors	i-MIEV
Fisker Automotive	A123 Systems	A123 Systems			Fisker Automotive	Karma
Daimler	Johnson Controls-Saft	Johnson Controls-Saft	Continental AG		Daimler	Mercedez-Benz S400 Hybrid
BMW	Johnson Controls-Saft	Johnson Controls-Saft	Continental AG		BMW	ActiveHybrid 7
Ford	Johnson Controls-Saft	Johnson Controls-Saft	Azure Dynamics			Transit Connect
Ford	?	?	?		Ford	Focus Electric

🟦 **Vertical Integration**
🟧 **Partnerships**
🟥 **Outsourcing**

Figure 23: Existing Supply Chain Relations in the Electric Vehicle Industry

As Tesla established itself as market leader, these relationships became easier to establish and the automaker's major cell supplier today is the Japanese cell manufacturer Panasonic. While the cells are procured from an external vendor, Tesla controls the technology around the cells and develops the remainder of the battery in-house. By doing so, company engineers are able to build knowledge in battery pack control and integration. Outsourcing the development of the battery pack would sacrifice that knowledge. The company considers the entire battery value chain to be very critical. A battery pack cannot deliver good performance without powerful and reliable cells. But, clearly, cells are not enough. The way these elementary components are assembled into modules, and then into a pack, is equally important to ensure an efficient and safe system. The automaker was also driven to develop its own technology for another reason. As mentioned earlier, Tesla was the first to develop and commercialize a highway-capable all-electric vehicle. A large portion of the technology involved had not been developed yet, especially battery packs of the necessary size and a battery management system including thermal management and the underlying software. The automaker therefore had to build its own battery pack and software because no one else in the industry could. As a result, Tesla was able to make significant breakthroughs in electric drivetrain technology and energy storage, breakthroughs that enabled the automaker to supply its technology to other OEM's, such as Daimler for its Smart electric fleet.

General Motors is another pioneer in the electric vehicle industry. Its plug-in hybrid, the Chevrolet Volt, will enter the U.S. market in 2011. This car, which has a 40-mile all-electric range, is equipped with a 16 kWh lithium-ion battery containing 220 cells. A123 Systems and LG Chem were both cell supplier candidates for GM. The automaker finally elected to use LG Chem's manganese spinel based cells. The cells will be manufactured in South Korea by LG Chem and shipped to the United States by sea and land in order to keep costs down. The battery packs will then be assembled at a purpose-built facility in Brownstown Township, Michigan owned and operated by General Motors. The automaker has also recently spent $8 million to double the size of its Global Battery Systems Lab, which is intended to test lithium-ion cells and packs and advance battery development. According to Tom Stephens, GM vice chairman in charge of global product operations, the three building blocks of any electric vehicle are the battery, the electric motor and the electronics that control the way the battery interacts with the motor: "Electric motors, batteries, power-control electronics, you need core expertise in those." General Motors is planning to develop production capability for all three components, by bringing nearly every segment of the chain, with the exception of battery cells, in-house through acquisitions. Another key factor is the parameters at which the battery operates, according to Robert Kruse, GM's executive director of global vehicle engineering for hybrids, electric vehicles and batteries (Clayton 2009a). The maximum and minimum states of charge, as well as the minimum and maximum operating temperatures, are highly valued intellectual property. Not only the parameters but the algorithms involved are also regarded as highly prized intellectual property. Being able to balance the cells as the pack ages is critical to ensuring the longevity of the battery pack. The automaker is also planning to introduce a Buick plug-in hybrid crossover a few months after the release of the Volt. The vehicle will incorporate the same technology and supply chain as the Volt.

Ford Motor Company is also planning to electrify its fleet by delivering four different electric vehicles to the United States market by 2012. While the electric drivetrains and battery systems for the first two vehicles will be outsourced for the most part, Ford plans to design, manufacture and integrate most of the drivetrain including the battery pack in-house. The latter two vehicles, which will be introduced in 2012, are a next-generation hybrid and a plug-in hybrid vehicle. Nancy Gioia, Director of Global Electrification for Ford, considers battery system design and development to be a "core competency for the company in the 21st century." For these vehicles, the design and development of the battery systems and the manufacturing process will be handled by Ford. How the battery is integrated into the vehicle is very important, and Ford perceives that it can build on many aspects of its expertise in the field, such as crash performance modeling and analysis. The automaker has always developed all of the software that goes into the vehicle, from engine software to safety systems. Similarly, it develops all the electrification software to ensure an integrated solution that optimizes cost and functionality. As it has achieved with its hybrid fleet, the company expects to achieve a 30% cost reduction in its electric drivetrain (including motor, battery, power electronics, etc.) based on a capital efficient and flexible strategy. Ford's strategy consists of using its highest volume global platform, which produces more than 2 million vehicles each year, to build its electric fleet. Instead of having a dedicated platform for electric vehicles, as other automakers have done, the company plans to leverage the operations of its high-volume platform to reduce costs and increase capital efficiency. Another approach to achieve this cost reduction is to develop an efficient design or architecture that relies on the best technology available at the time, which will result in an incremental cost reduction through high volume. Economies of scale also allow Ford to reduce costs in other ways. The automaker already purchases millions of electronic controllers for various systems in the vehicle. By developing the battery management system in-house, the company can leverage its buying power to further reduce costs.

Some car manufacturers are making their way into the battery business, and conversely, some battery manufacturers are heading into the car business. BYD, originally a Chinese battery manufacturer, is seeking to establish itself in the electric car industry. BYD Auto Co. was born in 2003, a year after the acquisition of Qinchuan Automobile Co, a Chinese state-owned car company. As of 2008, the BYD sedan called the F3 became the bestselling sedan in China, topping well-known brands like the Toyota Corolla and Volkswagen Jetta. The company was also the first to introduce a mass-produced plug-in hybrid vehicle to the market during that same year and plans to introduce an all-electric vehicle in the next two years. By reverse engineering products made by others, BYD pushed its way into manufacturing production, eventually expanding upstream and downstream in chosen fields to build a profitable, vertically integrated enterprise (Dongmei et al. 2010). The company typically makes one or two large orders of models, materials or components, and then starts manufacturing them in-house. This approach allowed BYD to thrive in the battery business, overtaking Japanese battery leader Sanyo in just a few years to become the world's largest supplier of Nickel-Cadmium batteries, and eventually becoming the second largest supplier of lithium-ion batteries. When it entered the automotive industry, BYD went against the industry trend of outsourcing and developed a vertically integrated enterprise, allowing it to cut the cost of a vehicle by more than one-third. Nearly all of the components, from interior-trim pieces to engines, used in the manufacture of BYD automobiles, except for the tires and windshield glass are made by the company itself, reducing cost in every single component. Manufacturing an electric vehicle has its challenges, however. The giant battery maker is still struggling to mass-produce battery-powered cars at low cost that can guarantee safety. By producing its battery cells using manual labor, the company is sacrificing quality and consistency – which ensure safety – for lower cost. While BYD produces single cells with distinct advantages in terms of low cost, the integrated automaker has yet to develop sufficient knowledge and expertise in battery pack management, electronic control technology and vehicle integration technology, essential to a successfully marketable product.

Vertically integrated structures provide multiple benefits. By enabling tightly knit and efficient supply chain coordination, they provide many cost-cutting opportunities. A company is able to apply its expertise in cost engineering to its entire supply chain to drive cost-reductions. For automakers that operate at high volumes, integrating a portion of the supply chain internally allows cost efficiencies through economies of scale. In the particular case of electric vehicles, a company that develops the battery pack in-house acquires significant knowledge in battery technology both in terms of cell characteristics and pack assembly. This knowledge might prove to be crucial in driving innovation in battery pack management. This model is also very beneficial for first-movers. Looking back at the first-generation Toyota Prius, the Japanese carmaker was able to introduce the vehicle to the market as early as 1997 mainly by producing the key components such as the inverter, power module and electronic control units in-house (Automotive Industries 2004b). If Toyota had relied on suppliers such as Denso Corp. and Aisin Seiki Co., it probably would have taken the automaker several additional years to bring the car to market. Tesla Motors was faced with a similar situation. By developing its core technology (including the battery pack and motor) in-house, it was able to deliver the first highway-capable all-electric vehicle as early as 2006.

Vertical integration also exhibits some drawbacks. It often requires significant capital investments that are only profitable at high volumes. Looking back at the electric vehicle industry, such high volumes may not be achieved for a couple of years, thus delaying any returns from such an investment. Such a structure might also turn out to be quite rigid when it comes to benefiting from the best emerging technologies in the market.

Partnerships: Developing Batteries with Battery Supplier

Many companies turn to partnerships to strengthen supply chain integration and provide sustainable competitive advantage by providing opportunities to leverage unique skills and "locking-out" competitors (Lambert et al. 1996). A partnership consists of a closer, more integrated relationship, based on mutual trust, openness, shared risks and rewards, yielding results that would exceed those achieved by the firms individually. A joint venture is an even tighter relationship, which entails some degree of shared ownership across the two parties. Many automakers have developed strong relationships with battery manufacturers either through alliances or joint ventures. These include Toyota Motors, Nissan Motors and Fisker Automotive among others.

Toyota has partnered with Panasonic to form the joint venture Panasonic Electric Vehicle Energy Company, in which Toyota has a 60% share. Panasonic EV Energy Co. was established in 1996, in response to Toyota's need for nickel metal hydride batteries for its hybrid vehicles. The company also developed the battery ECU units that control the HEV battery pack systems. The ECU integrates detection and control units to measure temperatures and voltages of the pack system and control charge and discharge operations to ensure safety and reliability. The joint venture also supplies batteries for General Motors and Chrysler's hybrid vehicles. In 2009, Panasonic acquired one of its main competitors Sanyo, which was better positioned in the lithium-ion battery market. The joint venture is also planning to manufacture the lithium-ion batteries that are to be used in future Toyota electric vehicles.

Nissan has also leveraged a strong partnership with Japanese battery maker NEC to accelerate its entry into the electric vehicle industry. The automaker was among the first to pursue efforts in lithium-ion batteries for automotive applications, which began in 1992 when the chemistry was first commercialized. In 1997, the automaker developed the Nissan Altra, its first electric vehicle prototype with an integrated lithium-ion battery pack. The technology was not commercially viable at that point. In 2007, Nissan-Renault partnered with longtime partner NEC to form the joint venture Automotive Energy Supply Corporation (AESC) and announced a joint investment of $1 billion to develop batteries for its all-electric Leaf and future electric vehicles in its fleet. NEC has been developing batteries for mobile phones since the early 1990's and started development of automotive batteries in 1998. Nissan had made a breakthrough in cell technology by developing laminate cells based on a manganese-oxide chemistry. The joint venture aims to combine Nissan's cell technology and pack design with NEC's manufacturing expertise and ability to scale to high volumes. Since its inception, the venture has acquired considerable experience in battery pack design, development and testing. The first product to emerge from the two-company venture is the battery pack for the all-electric Nissan Leaf, one of the first all-electric vehicles to be commercialized, with sales beginning in 2010. The air-cooled 24-kWh battery pack, which is located under the floor of the rear cabin, consists of 48 modules each holding 4 stacked laminar cells based on the manganese-oxide chemistry developed by Nissan. Carlos Ghosn, Nissan's CEO, stated that the automaker seeks to establish control in the value chain of every strategic component that goes into the vehicle from the electric motor to the battery pack and battery management system. By investing vertically in its supply base, the automaker plans to leverage its control to drive technological breakthroughs and cost reductions instead of depending on external suppliers to take these initiatives. Nissan believes that developing and commercializing electric vehicles is a mass-market play and is therefore investing heavily in production capability to benefit from further cost efficiencies at high volumes. For the first two years, Nissan will be producing the Leaf in its plant in Japan which has a capacity of 50,000 vehicles per year. By the end of 2012, its plant in Tennessee, U.S. is expected to be ready for production with a capacity of 200,000 vehicles per year. Nissan is also partnering with American battery maker EnerDel to monitor other emerging chemistries in battery technology.

Other companies have also forged similar alliances. Mitsubishi Motors has partnered with GS Yuasa, the world's third-largest car battery maker, to form the joint venture Lithium Energy Japan. The venture produces the batteries for the i-Miev, which will be sold in Japan and Europe in 2010 and in the United States in 2011. It will be spending more than $400 million to build its third lithium ion battery plant in Japan, anticipating growing demand in its electric vehicles market. The venture is 51% owned by GS Yuasa, with Mitsubishi Corp holding 34% and Mitsubishi Motors 15%. The joint venture will leverage each company's strengths in vertical value chains, covering natural resources, materials, development and manufacturing.

Daimler has also established a joint venture with Evonik Industries, called Deutsche Accumotive. The venture will focus on research, development, production and system integration of battery systems based on lithium-ion technology. Production will start in early 2011 with the first production applications in Mercedes cars beginning a year later. Daimler owns 90% of the venture while Evonik owns the remaining 10%.

Fisker Automotive has also forged an alliance with battery maker A123 Systems. The venture-backed automaker was founded in 2007 by Fisker Coachbuild, LLC and tier-one supplier Quantum Technologies. The company is developing a 50-mile plug-in hybrid called the Karma, scheduled to launch by the end of 2010. The hybrid system called Q-Drive, supplied by Quantum Technologies, features two rear-wheel electric motors, and a 2-liter GM Ecotec engine. The 23-kWh battery pack, which runs longitudinally down the center of the car, will be provided by A123 Systems. The battery company plans to manufacture the cells and systems at its Livonia facility in Michigan, with production scheduled for late 2010. Quantum Technologies will add its proprietary controls software into the vehicle control unit to handle the real time control of the multiple powertrain systems including the power management of the battery. According to Henrik Fisker, Fisker Automotive's CEO, the automaker selected A123 because of the company's ability to meet our performance needs and rapidly scale to their production volume." In addition to entering into the supply agreement, A123 Systems will be investing up to $23 million in the automaker's current funding round, with the aim of establishing a strategic relationship with the car company.

Partnerships may be a very advantageous model of interaction between automakers and cell manufacturers as it allows them to synergize their core competencies. The battery manufacturer provides the cell technology and gathers input from the automaker to customize the modules and battery pack. Both sides work closely together to develop the optimal product according to the design specifications of the vehicle. Where joint ventures are involved, automakers can also influence the battery maker's supply chain by applying its cost-reduction capabilities.

Such relations may also have some disadvantages. In such situations, the car manufacturer is more or less restricted to the technology provided by the cell manufacturer and therefore cannot react quickly to technological advances achieved by other cell suppliers. Additionally, such exclusive agreements may limit the automaker's capability of scaling up to that of the battery supplier.

Outsourcing: Contracting Battery Development To External Supplier

In the third type of relationship, the automaker outsources the development of the battery system to an external supplier which tends to be a tier-one supplier. This model is often referred to in the literature as "arm's length". Such relationships are perhaps the most predominant type of supply chain interactions in the auto industry, whereby a seller typically offers standard products/services to a wide range of customers who receive standard terms and conditions (Lambert et al. 1996). Either a single transaction could occur, or multiple exchanges ranging over a longer period of time may be involved. Supplier selection often occurs through competitive bidding.

In this model, automakers typically outsource the development and manufacturing of the battery pack to a tier-one supplier that has an established relationship with the battery industry. In fact, many tier-one suppliers have teamed up with cell manufacturers. Johnson Control has made an agreement with Saft in the United States, hoping to combine Johnson Control's manufacturing expertise with Saft's technical knowledge in cell technology. LiMotive is another joint venture between South Korean cell manufacturer Samsung SDI and German tier-one supplier Bosch. Such relations enable tier one suppliers to take advantage of their automotive-integration expertise to the battery business and give cell manufacturers access to multiple car manufacturers (Boston Consulting Group 2009a). Automakers to whom this model applies include Daimler, BMW and Ford.

Daimler launched one of the first commercial vehicles to use a lithium-ion battery pack in 2009 with the Mercedes-Benz S400 Hybride. The lithium-ion cells were supplied by Johnson Controls-Saft, and the pack was assembled by Continental AG, a German tier-one supplier which also supplied the corresponding power electronics, including a master control unit, which acts as the master of the E-drive system, an inverter and a DC/DC converter. Mercedes-Benz was able to fit the 35-cell 0.8 kWh pack into the same space (at the right-hand base of the windshield) that used to hold the standard lead-acid starter battery. The designers didn't have to make a single change to the body structure. However, to keep the battery temperature below 25 degrees Celsius, the pack had to be integrated into the S-Class climate control system. Air-conditioning coolant pipes run right through the pack to maintain it at temperatures between 15 and 35 degrees Celsius. The German automaker BMW will be using a very similar technology from the same suppliers for its ActiveHybrid 7 due to be launched in 2011. The major difference is that the battery pack will be installed underneath the trunk floor between the wheel arches of the vehicle, safely surrounded by a high-strength special casing.

Ford is also outsourcing the design and development of the electric drivetrain of its first two electric vehicles, the Transit Connect to be launched in 2010 and the Focus Electric to follow in 2011. The Transit Connect is an all-electric commercial vehicle that will be developed in collaboration with Azure Dynamics. The vehicle will be built by Ford in Turkey, and will be shipped to the United States as 'gliders' (i.e., without a powertrain). Once in Detroit, Azure Dynamics will install the electric drive system, including power electronics and battery system, which will include cells manufactured by Johnson Controls-Saft. The all-electric Focus will be developed in partnership with Magna International. Magna will supply some of the components involved in the powertrain and perform some of the systems integration while Ford will be working with a cell manufacturer to supply and integrate the battery pack. Ford realizes that it is most cost effective at high volume as it can benefit from economies of scale. It has therefore sought to outsource the development and manufacturing of its first electric vehicle drivetrains because it expects low volumes during the first few years of commercialization. As such it has established strong relationships with suppliers such as Azure Dynamics and Magna International.

Outsourcing the development and manufacturing of the battery pack clearly has its benefits. First, automakers avoid large capital investments to develop in-house capabilities and can therefore operate easily at lower volumes. They can also leverage a cross-manufacturer supply base and benefit from scaling effects. Moreover, automakers are not restricted to a particular supplier or technology and can thus easily switch to a different technology should one arise.

However such a structure forces automakers to sacrifice knowledge and control of the technology. At any given point, they only have access to the best technology that is used by other automakers and therefore can hardly establish any competitive edge from a technical standpoint. Outsourcing also increases dependence on the capabilities of the supplier. An automaker's product is only as competitive, cost-effective and scalable as that of its supplier.

Before proceeding to a discussion of the impact all three models have on the competitiveness of automakers, it is important to understand how the battery interacts with the rest of the vehicle, raising the question: How modular is the battery pack in an electric vehicle?

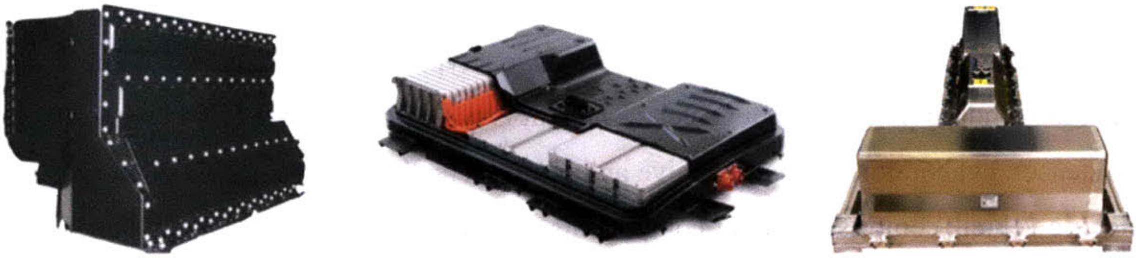
How Modular Is The Battery Pack?

The degree of modularity of the battery pack, which depends on its form factor and the simplicity or complexity of the interactions it has with the rest of the vehicle, will strongly influence how the supply chain is structured. A very modular component allows for simpler supplier relations, while an integrated component is likely to require more intricate relationships necessitating the exchange of tacit as well as codified information.

Figure 24 shows the battery packs for three electric vehicles: the Tesla Roadster, the Nissan Leaf and the Chevrolet Volt. The three battery packs have very different form factors. The Roadster has a box-shaped pack that extends in the vertical direction and is located behind the seats, the Leaf has a flatter pack that extends horizontally and is placed underneath the rear-passenger seats, while the Chevy Volt has a T-shaped pack that is integrated into the vehicle chassis. The battery pack itself is fairly modular by nature. Assembled from a series of modules, car designers and engineers have the flexibility to customize its form factor to integrate it in different regions of the vehicle as seen earlier.

Figure 25 shows a schematic of an electric vehicle drivetrain. The battery essentially interacts with three different systems. First, the power system (in red) carries the flow of electricity. The battery receives power from the battery control unit, which is connected to the external charger, and feeds it to the powertrain controller that transmits it to the electric motor. These processes are overseen and controlled by a monitoring and control system (in green). The battery monitoring unit collects data from the battery such as voltage and temperature, processes it and sends control instructions to the battery control unit to allow charging, discharging, etc or to the thermal management system (in blue) to regulate temperature. The thermal management system is in charge of maintaining the battery pack within an acceptable temperature range. The unit receives instructions from the battery monitoring unit and pumps a fluid (either liquid or air) to either cool the battery pack to prevent it from overheating or warm the pack in low ambient temperatures.

The power system is fairly comparable to the one present in commercial hybrid vehicles. The main difference is that in the latter the battery pack is much smaller and relies on a nickel metal hydride chemistry. The interactions of the battery with the remaining components of the drivetrain, which essentially consist of flows of electricity, are quite similar however. Using the Toyota Prius as an example, the battery is supplied by Matsushita Battery Industrial Co., better known as Panasonic, while the automaker manufactures components of the power system in-house. It makes the car's Atkinson-cycle gasoline engine at its Kamigo plant, the motor, generator and power-split device at its Honsha plant, and key electronic components such as the power module and brake regeneration and power steering controllers at its Hirose plant (Automotive Industries 2004b). Meanwhile Denso Corp., Toyota's main electronics supplier, provides the battery ECU (Electronic Control Unit), current sensor and electrical inverter air-conditioning system. Other suppliers also include Yazaki Corp. and Sumitomo Wiring Systems Ltd., which divide the car’s high-voltage wiring, and Aisin AW Co., a subsidiary of Aisin Seiki, which supplies the CVT (Continuously Variable Transmission). Toyota was compelled to produce some of the key system components in-house since it was the first to develop a hybrid technology and no supplier had either the knowledge or expertise to do so. Many other automakers that produce hybrid vehicles rely either on Toyota’s technology such as Nissan and Ford or other suppliers such as Honda. In all cases, the battery for almost all hybrid vehicles is typically supplied by Japanese manufacturers Panasonic or Sanyo, confirming its modularity within the power system.



(a) Tesla Roadster

(b) Nissan Leaf

(c) Chevrolet Volt

Figure 24: Battery packs for (a) Tesla Roadster, (b) Nissan Leaf and (c) Chevrolet Volt

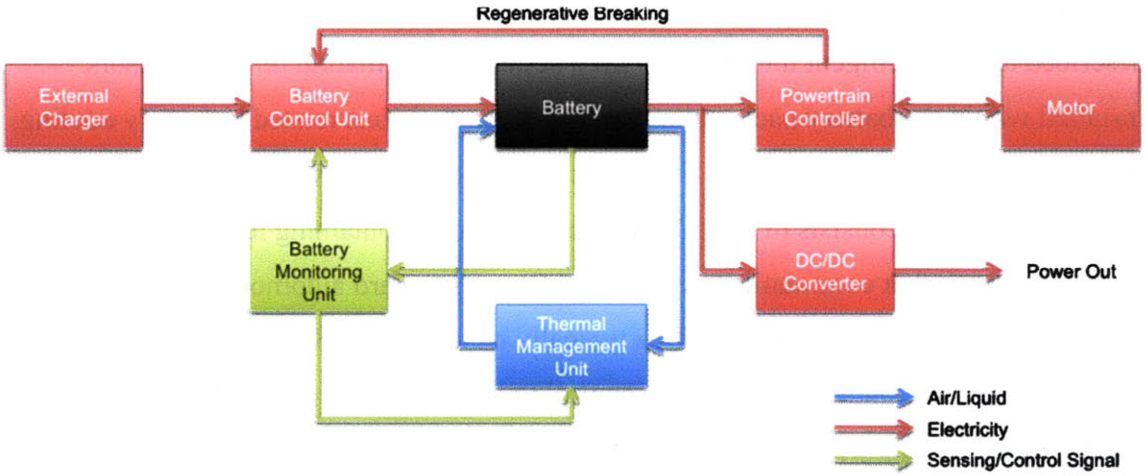


Figure 25: Electric Vehicle Drivetrain Schematic

Complexities arise with the introduction of a bigger lithium-ion battery pack, which requires an elaborate battery management system for plug-in hybrid and all-electric vehicles. Incorporating a smart monitoring system and a thermal management system results in a much more intricate drivetrain with all three systems (power, control and thermal management) interacting together.

The thermal management system can be related to a typical HVAC (Heating, Ventilating, and Air Conditioning) unit in a vehicle. The unit is typically composed of a compressor, condenser, evaporator, regulating valve and piping. The thermal management unit in an electric vehicle comprises similar components, whereby pipes run through the battery pack via sealed fluid paths to allow for effective heat exchange. Looking at the supply chain for HVAC units, the system is almost entirely outsourced to external suppliers. In Toyota's case, Denso, which has established a global leadership position in automotive air conditioning, produces and assembles HVAC units for nearly its entire car lineup (Automotive Industries 2004a). Within the thermal management system, the battery can be considered to be modular.

The remaining system, which consists of a battery monitoring and control unit, is often described as the intelligent unit. It reads off a series of information through sensors installed within the battery pack and makes real time decisions related to battery cooling, state of charge, and battery faults. The unit is composed of hardware and software. The hardware basically consists of an ECU, a small computer containing multiple microprocessors that communicate via a CAN Bus, a standard automotive communication protocol. The CAN Bus typically handles up to 80 ECU's responsible for various operations ranging from engine control to airbag control and on-board diagnostics. ECU's are provided by external suppliers. For the Prius, Denso Corp. provides the ECU for the hybrid system. ECU hardware is known to be modular as it is independently created and very easily integrated into the system. The accompanying software is generally also provided by the ECU supplier as applications tend to include rather simple operations such as body control (controls door locks, electric windows, courtesy lights, etc.) or on-board diagnostics (provides state of health information for various vehicle sub-systems).

In the case of a plug-in hybrid or all-electric vehicle, the software containing all the algorithms that monitor and control the battery pack and powertrain is regarded as one of the most valuable elements from an IP standpoint. Given that these sophisticated powertrains, which rely on lithium-ion-based battery packs, are still in their embryonic stages, optimization of their technologies is far from being achieved. Therefore the approach in managing individual components could result in significant advantage over the competition. For example, Ford credits the incremental fuel efficiency of its Fusion hybrid over the Toyota Camry to an adequate system integration based on software optimization, given that all the hardware is practically the same. For the bigger battery packs present in plug-in hybrids and all-electric vehicles, the state of charge of lithium-ion batteries affects significantly their lifespan. Appropriate monitoring and control of that parameter can provide tremendous leverage on initial design and performance. Over-sizing of the battery, which can prove to be significantly costly, can thus be avoided, and a long lifespan of the battery can be ensured. What is particularly instrumental in the software is not the algorithm or logic, but rather the tuning and cut-off parameters that require a fundamental understanding of the cell behavior. Given that this software is involved in all systems (power, control and thermal management) connected to the battery pack, it can hardly be conceived by any of the battery supplier, powertrain supplier, HVAC supplier or electronic supplier alone. The only exceptions are tier-one suppliers that actually provide all of these systems and can thus design the software within an integrated solution. Tier-one suppliers capable of offering such a product are very limited however and include companies such as Johnson Controls-Saft, Denso Corp. and Continental AG. So while the hardware of the control unit is quite modular, its software is much less so. Many OEM's are recognizing that they will have to develop it if they are to have a competitive edge.

Going back to the initial question of the battery pack's modularity, the pack itself seems modular, as does the hardware involved in the powertrain, control and thermal management. The software, however, which is undoubtedly a key factor for competitive advantage, is a much more integrated element and is likely to be better if performed by the vehicle integrator.

Implications on Competitiveness of Automakers

Competition for what is projected to be a $25 billion market for electric-car batteries in 2020 (Boston Consulting Group 2009a) is already in progress along the industry value chain. The critical importance of batteries in overall vehicle performance enables battery manufacturers to greatly influence the car industry and its players. Batteries will give car companies their competitive edge. They will determine how fast a car can accelerate, how far it will go on a single charge, how quickly it can recharge, and, since it accounts for as much as half the cost of an all-electric vehicle, how much it costs. Therefore the relationships between battery suppliers and automakers are crucial in establishing the automakers' competitiveness. As noted earlier, all three models of interaction have their own strengths and weaknesses. This section aims to shed light on the implications of each model on the competitiveness of automakers.

The implications of each model for the automakers' competitiveness is also affected by the development of the industry. For instance, the emergence of a winning chemistry or the standardization of the battery pack would have important repercussions on automakers depending on how their value chain is structured. Implications are also likely to vary as high volumes are achieved. Hence, we should take into account factors such as industry life-cycle, demand, and economies of scale. We therefore distinguish the repercussions of all three models based on a time scale of short-term and long-term, to account for the evolution of the industry. Short-term considerations have a scope of 5 to 10 years while long-term considerations are for 10 years and more.

Short-term Implications

Cells are not the highest value-added component in the battery. Everyone can have access to the best performing cells in the market, be it Panasonic, LG Chem or A123 Systems which is manufacturing them. Real value lies in how these cells are assembled and configured to form a battery pack. Knowledge of the cell properties, however, is crucial as it allows extracting the optimal performance of these cells while maintaining safety and reliability. This can be achieved either through strategic partnerships with cell manufacturers or by rigorous testing in the lab. Only then can appropriate feedback be given to cell manufacturers to further improve their cells and perhaps adapt them to the particular needs of the automaker.

Whether the battery pack should be built in-house or not depends on multiple factors.

In the case of first-movers, most are compelled to develop and manufacture the technology in-house for two main reasons. First, given their pioneering role in the industry, it is unlikely that an external supplier will have adequate knowledge and expertise. Second, first-movers are very hesitant to share their innovative technologies with external suppliers and run the risk of a leak to competitors and lose competitive advantage. This was the case of Toyota and Honda with hybrid technologies in the late 1990's and Tesla Motors with its all-electric Roadster in the early 2000's. Tesla prides itself on having the best performing battery pack in the industry and claims that competitors will need years to catch up.

Players who are better off outsourcing the development of the battery pack to external suppliers are startups and companies in their early stages with low volumes. Automakers such as Fisker Automotive, with limited resources to invest in battery manufacturing capability, are likely to find it more strategic to either partner with a battery maker or outsource its entire drivetrain to a tier-one supplier.

On the other hand, automakers which are looking to become major players in the electric vehicle industry and scale up to high volumes rapidly will find it more strategic to either invest in a vertically integrated supply chain or partner with a battery maker that can accommodate the automaker's requirements of scaling up while maintaining high quality standards. Such strategies will allow big industry players to capture market share early on and achieve cost reductions by benefiting from control of their supply chain and economies of scale.

Companies that are rather bearish vis-à-vis the outlook of the electric vehicle industry might hedge their liability by partnering with battery makers to minimize capital investments while the outlook of the industry becomes clearer. But when the market picks up – should it ever pick up – they would have lost any competitive advantage stemming from the ability to quickly reach economies of scale and to benefit from cost reductions early on.

Long-term Implications

The implications for automakers' competitiveness depend strongly on how the battery pack evolves. If the industry embraces standardization of the battery pack or reaches consensus on a single chemistry, it is very likely that tier-one suppliers will assume the development of battery packs as is observed with other standardized vehicle components such as the HVAC system or control modules.

However, based on the interviews and discussions conducted in this research, standardization of the battery pack seems unlikely. Both form factor and pack characteristics allow the automaker to differentiate its vehicle, in terms of performance, range, cost, and safety among others. There have been many efforts in the electronics industry to standardize the batteries for laptop computers and mobile phones. These efforts were unsuccessful given that the battery was perhaps the most versatile component in terms of form factor. While older battery technologies required electronic companies to design their products around the battery, the introduction of lithium-ion battery technology has enabled the customization of these batteries by adapting them into the product. Similarly, in electric vehicles, the versatility of the battery pack form factor allows the car engineers to place the pack in different locations in the vehicle such as behind the passengers, along the centerline of the chassis or under the rear-passengers.

There are about 5 different chemistries proposed for lithium-ion batteries. Each has its own advantages in terms of cost structure, power performance, thermal characteristics, etc. It does not seem likely that there will be a convergence in the industry towards a single chemistry. In terms of functionality, the battery pack can be compared to the internal combustion engine. Just as the engine defines the performance of the vehicle, the battery defines the performance of an electric vehicle. Some engines are designed for fuel-efficiency, while others are fitted for high performance. Similar market differentiation is likely in the electric vehicle industry. Some lithium-ion chemistries are better suited for lower cost structures, while others have a higher price tag, but have a better power performance. That being said, as more money is invested into battery research and development, many breakthroughs will be achieved, driving the optimization of some of those chemistries. Currently the rate of improvement is averaging around 8% annually with respect either to cost decreases or increases in capacity.

As the technology matures, and batteries become marginally differentiated, the focus of innovation will shift towards to the optimization of the battery pack. Hybrid drivetrains are a good example of this. Hybrid technology, first developed in the late 1990's, has now reached a mature phase in its lifecycle. All automakers use the same hardware and the same batteries, provided by a handful of suppliers. They seek to differentiate themselves through the software, which controls how the hardware is managed. For example, Ford was able to achieve a better fuel efficiency in its Fusion hybrid than the Toyota Camry by optimizing the software. A similar trend is expected to take place in the electric vehicle industry. Proper battery management through software innovation will allow for better performance, longer ranges, more efficient designs and thus lower costs, as well as safe and reliable systems.

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Section 5 – Government Role and Policy

As discussed in Chapter 1, nations around the world are seeking to transform their energy systems to strengthen their energy security, meet soaring demand, mitigate climate change and in some cases stimulate struggling economies. The United States is seeking to reduce its consumption of foreign fossil fuels and achieve greater energy security, and the current administration has even identified an opportunity to revive the struggling U.S. economy by tapping into the energy industry. European nations are more concerned about global climate change and were the first to raise awareness and try to mitigate carbon emissions. Emerging economies such as China and India are preoccupied with meeting their rapidly increasing energy demand. While the particular motivations might differ across regions and economies, every major nation is seeking less energy intensive technologies that rely less on fossil fuels and emit less carbon. Governments therefore need to take active measures to shape their energy future, for which the transportation sector anticipates vehicle electrification.

As noted earlier, the electric vehicle industry faces many hurdles, including high costs, technological limitations, and an undeveloped infrastructure to name a few. Many governments have intervened by dedicating additional efforts and resources to overcome these challenges. In the United States, the Obama administration has invested billions of dollars to support the electric vehicle industry and has set a revised target of an annual production of 500,000 plug-in hybrid vehicles by 2015[10]. Michigan has offered hundreds of millions of dollars in tax credits to battery manufacturers, aiming to become "the battery capital of the world", according to its governor Jennifer Granholm. China publicly announced its intention to become the leading producer of hybrid and all-electric vehicles by 2015. Public policy will play a major role in both the advancement of battery technologies and the deployment of electric vehicles into the market. This section describes the mechanisms through which governments take part in shaping the industry.

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[10] The initial target of the Obama administration was to put one million plug-in hybrid vehicles on the road by 2015.

In order to promote electric vehicle adoption and achieve the objectives mentioned above, government has several options. On one hand, it can support the development of innovative technologies and ensure that appropriate conditions are met for manufacturers to produce competitively (technology push), and on the other, it can stimulate the market for electric vehicles and encourage customer adoption (market pull).

Technology Push

Technological development will undoubtedly enable cheaper and higher-performing batteries that will accelerate the mass deployment of electric vehicles. The government can play an important role in advancing battery development through multiple channels. The U.S. Department of Energy has established many public-private partnerships that target battery development, a dedicated battery research and development program under the Vehicle Technologies Program (VTP) within the Energy Efficiency and Renewable Energy branch. Under the recent American Recovery and Reinvestment Act of 2009, the U.S. government has dedicated funding to support battery manufacturing and the deployment of electric vehicles under the Advanced Battery Manufacturing and Transportation Electrification programs, in addition to previous efforts that supported the manufacturing of electric vehicles such as the Advanced Technology Vehicle Manufacturing Loan program. Other efforts also include the Advanced Research Projects Agency-Energy (ARPA-E) program, which funds numerous projects that target the development of transformative battery technologies for transport applications.

Public-Private Initiatives

Many initiatives between the government and private companies have been launched since the 1990's to promote the deployment of electric vehicles and the development of lithium-ion battery technology.

Perhaps the first public-private initiative to take place in the industry was the United States Council for Automotive Research (USCAR), a collaboration between the U.S. Department of Energy and the three American automakers, Chrysler, Ford and General Motors. Founded in 1992, the goal of USCAR was to further strengthen the technology base of the U.S. auto industry through cooperative research and development. The United States Advanced Battery Consortium (USABC) was established under the USCAR's umbrella, to foster the development of advanced batteries for electric vehicles. It aims to engage automakers, battery manufacturers, national laboratories, universities, and other key stakeholders in achieving performance targets that would enable the commercialization and mass deployment of hybrid and electric vehicles. Not only does the consortium award research grants to develop advanced batteries that serve the electric vehicle industry, it also defines performance targets for the development of these batteries including technical characteristics and cost.

The Partnership for a New Generation of Vehicles (PNGV) was another initiative by the U.S. federal government to support the development of next-generation vehicles with high fuel efficiencies (up to 80 miles per gallon). Established in 1993 by the Clinton administration, the partnership involved 8 federal agencies, national laboratories, universities and the United States Council for Automotive Research (USCAR). Various approaches were identified to reach the targeted fuel-efficiencies, including the reduction of vehicle weight, increasing engine efficiency, combining gasoline engines and electric motors in hybrid vehicles, implementing regenerative braking, and the use of efficient fuel cells. All three automakers presented prototypes in early 2000, but none of them were put into production. The 1993 initiative had alarmed European and Japanese automakers, which quickly began looking into cleaner and fuel-efficient technologies. German automaker Daimler AG decided to pursue fuel cell technology while Japanese companies invested in hybrids. Both Toyota and Honda had hybrid vehicles in the market by 1999. While the PNGV aimed to spur innovation in the American auto industry, Japanese manufacturers responded promptly and were the first to introduce hybrid technology to the U.S. market in 1999 and 2000. The PNGV was cancelled in 2001 by the Bush Administration and was replaced by the FreedomCar initiative that focused on the development of fuel cell-powered by hydrogen fuel.

The FreedomCAR and Fuel Partnership is a collaboration among the U.S. Department of Energy, USCAR, and five major energy companies, BP America, Chevron Corporation, ConocoPhillips, ExxonMobil Corporation and Shell Hydrogen. The goal of the collaboration is to develop emission- and petroleum-free cars and light trucks, by supporting research in high-risk technologies, such as hydrogen-powered fuel cells.

In 2010, the Department of Energy's congressional budget request cut funding for fuel cell technologies by 60% to $68.2 million. According to Secretary of Energy Steven Chu, the DOE is "moving away from funding vehicular hydrogen fuel cells to technologies with more immediate promise." In fact, the Department of Energy considers vehicle electrification a more promising path in the short term and has therefore invested significant resources in advancing battery technology and its manufacturing (Table 4).

Battery Research and Development

Many programs and initiatives targeting the development and integration of battery technologies stem from the U.S. Department of Energy. These efforts are executed by national research institutions, which work closely with industry and other beneficiaries to accomplish the goals set by the DOE. One of the core programs of the Office of Energy Efficiency and Renewable Energy (EERE) within the Department of Energy is the Vehicle Technologies Program (Table 4). The program aims to support research and development to make passenger and commercial vehicles more efficient and capable of operating on non-petroleum fuels. Among its efforts, the program focuses on transportation electrification activities, including the development of durable and affordable advanced batteries, power electronics, and electric motors for hybrid, plug-in hybrid and electric vehicles. The increased funding is aimed to support transportation electrification activities, including battery research and development and infrastructure development. As part of a new proposed structure, batteries and electric vehicles will have a dedicated budget line under the new Batteries and Electric Drive Technologies subprogram (formerly Hybrid Electric Systems), highlighting the strategic importance the DOE is according to electric transport. The Energy Storage R&D activity within the former Hybrid Electric Systems subprogram has also been renamed Battery/Energy Storage R&D", emphasizing the importance of battery research and development. The Battery/Energy Storage R&D activity supports the development of advanced batteries for hybrid, plug-in hybrid and electric vehicles, as well as the research and development of advanced materials that would enable next generation battery systems.

	FY 2009	FY 2009 (Recovery)	FY 2010	FY 2011[11]
Energy Efficiency and Renewable Energy	**2,156,865**	**16,771,907**	**2,242,500**	**2,355,473**
Vehicle Technologies	267,143	109,249	311,365	325,302
Batteries and Electric Drive Technology (formerly Hybrid Electric Systems)	101,572	-	101,405	120,637
Battery/Energy Storage R&D	69,425	-	76,271	93,992
Advanced Battery Manufacturing	-	1,990,000	-	-
Transportation Electrification	-	398,000	-	-
Advanced Research Projects Agency - Energy[12]	**15,000**	**388,856**	**0**	**299,966**
Science				
ARPA-E	6,300	-	-	-
Energy Transformation Acceleration Fund				
ARPA-E Projects	0	377,556	0	273,400
Program Direction	8,700	11,300	0	26,566
Advanced Technology Vehicle Manufacturing Loan Program	**7,510,000**	**10,000**	**20,000**	**9,998**
Direct Loan Subsidy Costs	7,500,000	-	-	-
Administrative Expenses	10,000	10,000	20,000	9,998
Science	**4,807,170**	**1,632,918**	**4,903,710**	**5,121,437**
Basic Energy Sciences	1,535,765	555,406	1,636,500	1,835,000
Energy Innovation Hub - Batteries and Energy Storage	-	-	-	34,000

Table 4: Department of Energy Budget Related to Batteries (in Thousands). Source: (DOE 2010a)

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[11] Congressional Request

[12] Note that not all of these projects are related to electric vehicles and battery developments. The ARPA-E budget is detailed susbsequently.

Most research and development efforts supported by the program are carried out by national laboratories, namely Argonne National Laboratories, the National Renewable Energy Laboratory, and Sandia National Laboratories. Argonne is the Department of Energy's lead laboratory for its applied research and development program for hybrid electric vehicle applications, the Advanced Technology Development program (ATD). This is a multi-laboratory program that involves support from four other DOE national laboratories: Brookhaven, Idaho, Lawrence Berkeley and Sandia. The objective of the program is to help industrial developers of lithium-ion batteries to overcome key technological challenges such as calendar life, abuse tolerance, low temperature performance and cost. Argonne is also involved in a longer-range research and development program, the Batteries for Advanced Transportation Technologies (BATT) program. The National Renewable Energy Laboratory (NREL) leads the Energy Storage Project, focusing on battery thermal management, modeling, and systems solutions to enhance the performance hybrid and electric vehicles. As part of DOE's Vehicle Technologies Program, NREL works closely with the U.S. Advanced Battery Consortium to pursue research and development on advanced energy systems that can provide future generations of electric vehicles. NREL is also involved in modeling and simulation to evaluate technical targets and energy storage parameters, and investigating combinations of energy storage systems to increase vehicle efficiency. Sandia's Battery Abuse Testing Laboratory (BATLab) is globally renowned for its advances in battery testing. The tests performed help to determine how much abuse lithium ion batteries can safely handle, ensuring they meet real-world performance requirements. Sandia has particularly played an instrumental role in ensuring the safety and reliability of the batteries that will power the Chevrolet Volt, expected to be introduced in 2011. The laboratory has recently received $4.2 million as part of the American Recovery and Reinvestment Act to modify and enhance its existing BATLab, with the ultimate goal of developing low-cost batteries for electric and plug-in hybrid electric vehicles.

Advanced Battery Manufacturing

As part of the American Recovery and Reinvestment Act (ARRA) of 2009, the Obama administration announced a series of 48 grants, amounting to $2.4 billion in funding, to accelerate the development of U.S. manufacturing capacity for batteries and electric drive components. These grants amount to more than the combined total of VC and private funding of the battery industry over the past 4 years (Bradford 2009). The bulk of the 48 grants, about $1.5 billion, will go to the development of battery technology and manufacturing capacity, covering the entire battery value chain from material and cell components supply to cell manufacturing, pack assembly and recycling (Figure 26). Another $500 million of grants will go to the companies that make other electric drivetrain components such as electric motors. The last $400 million will be spent on infrastructure concepts, funding research on basic technology and demonstration projects.

Winning companies are expected to match the sums received from the government with their own capital investments. According to the Department of Energy, the recipients were selected through a competitive process conducted by the DOE itself. However, John Goodenough, who reviewed some of the funding applications, stated that in his opinion the allocations were politically motivated: "I was very surprised at who got a fair amount of the money, [...] lobbying in Washington must have played a big role" (Dolgin 2009).

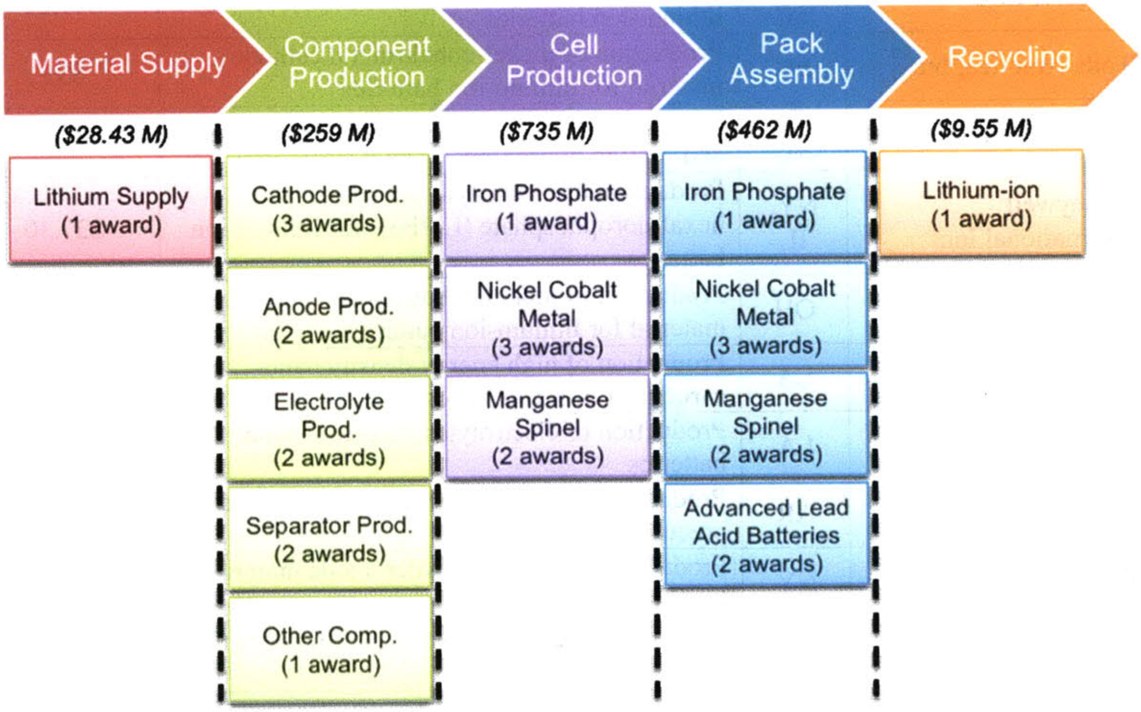

Figure 26: American Recovery and Reinvestment Act (ARRA) 2009 grants distribution for battery technology and manufacturing capacity. Source: (DOE 2010b)

Applicant	State	Technology	Grant (in Millions)
Cell, Battery, and Materials Manufacturing Facilities			
Johnson Controls, Inc.	MI, OR	Production of lithium-ion battery cells and packs	$299.20
A123 Systems, Inc.	MI	Manufacturing lithium-ion cells, modules and pack assembly	$249.10
KD ABG MI, LLC	MI	Production of lithium-ion batteries	$161
Compact Power, Inc.	MI	Production of lithium-ion polymer battery cells	$151
EnerDel, Inc.	IN	Production of lithium-ion cells and packs	$119
General Motors	MI	Production of high-volume battery packs	$106
Saft America, Inc.	FL	Production of lithium-ion cells, modules, and battery packs	$96
Exide Technologies with Axion Power International	TN, GA	Production of advanced lead-acid batteries	$34.30
East Penn Manufacturing Co.	PA	Production of the UltraBattery (lead-acid battery with a carbon supercapacitor combination)	$32.50
Advanced Battery Supplier Manufacturing Facilities			
Celgard, LLC	NC, SC	Production of polymer separator material for lithium-ion batteries	$49.20
Toda America, Inc.	SC	Production of nickel-cobalt-metal cathode material for lithium-ion batteries	$35
Chemetall Foote Corp.	NV, NC	Production of battery-grade lithium carbonate and lithium hydroxide	$28.40
Honeywell International Inc.	NY, IL	Production of electrolyte salt (lithium hexafluorophosphate (LiPF6)) for lithium-ion batteries	$27.30
BASF Catalysts, LLC	OH	Production of nickel-cobalt-metal cathode material for lithium-ion batteries	$24.60
EnerG2, Inc.	LA	Production of high energy density nano-carbon for ultracapacitors	$21
Novolyte Technologies, Inc.	LA	Production of electrolytes for lithium-ion batteries	$20.60
FutureFuel Chemical	AR	Production of high-temperature graphitized precursor	$12.60
Pyrotek, Inc.	NY	Production of carbon powder anode material for lithium-ion batteries	$11.30
H&T Waterbury DBA Bouffard Metal Goods	CT	Manufacturing of precision aluminum casings for cylindrical cells	$5
Advanced Lithium-Ion Battery Recycling Facilities			
TOXCO Incorporated	OH	Hydrothermal recycling of lithium-ion batteries	$9.50

Table 5: American Recovery and Reinvestment Act (ARRA) 2009 grants for battery technology and manufacturing capacity. Source: (DOE 2010b)

Out of the $1.5 billion dedicated to advanced battery manufacturing, the largest grant was awarded to the Michigan division of Johnson Controls, which received $299.2 million, followed by A123 Systems which received $249.1 million. Other lithium-ion battery manufacturers who received grants of more than $100 million included Dow Kokam, Compact Power, and EnerDel.

Out of the $2.4 billion, the "Big Three" carmakers (Chrysler, Ford and General Motors) were granted more than $400 million collectively, while companies located in the state of Michigan were awarded $1.4 billion.

Michigan has played an active role in attracting companies to the state, aiming to become the "advanced battery capital of the world", according to Governor Jennifer Granholm. Since 2006, the state has spent more than $700 million in tax incentives to attract and grow battery companies. Many companies have responded positively, especially since battery-manufacturing processes have become highly automated and thus labor costs are no longer a major concern. Johnson Controls-Saft received $148.5 million and KD Advanced Battery Group (Dow Kokam) received $146.6 million in tax credits. Compact Power has received $125.2 million in tax incentives to move its operations to Michigan and expand its advanced battery manufacturing capabilities. A123 Systems received $100 million worth of tax credits to shift its manufacturing from China to Michigan. In return, the four companies have pledged to invest a combined $1.7 billion in new lithium-ion battery factories in the state.

The Department of Energy has also established an Advanced Technology Vehicle Manufacturing Loan Program (ATVM Loan Program), which provides loans to automobile and automobile part manufacturers for the cost of re-equipping, expanding, or establishing manufacturing facilities in the United States to produce advanced technology vehicles or qualified components, and for associated engineering integration costs. Since its inception in 2007, the program has awarded five loans for a total of $8.5 billion. The loan commitments include $5.9 billion for Ford Motor Company to transform a series of factories designed to produce 13 more fuel efficient vehicles, $1.6 billion to Nissan North America to retool their factory in Tennessee to build electric vehicles and battery systems, $465 million to Tesla Motors to manufacture electric drive trains and electric vehicles in California, $24 million to Tenneco, Inc. to develop fuel efficient emission control components for advanced technology vehicles, and $528.7 million to Fisker Automotive for the development of two models of plug-in hybrids. As of January 2010, the ATVM Loan Program has closed on its loan offers to Ford Motor Company and Tesla Motors. The Department of Energy will not be seeking additional appropriations for credit subsidy costs in FY 2011.

Advanced Research Projects Agency-Energy (ARPA-E)

The government is also involved in battery research and development through the Advanced Research Projects Agency-Energy (ARPA-E). Modeled after DARPA (Defense Advanced Research Projects Agency), the agency aims to accelerate the development of next generation energy technologies. While the DOE invests heavily in conventional energy research, ARPA-E focuses on high risk-high payoff projects that are transformational by nature rather than evolutionary developments. In the area of energy storage for electric transport, the agency seeks to pursue projects that develop a new generation of battery technologies for long electric range plug-in hybrids and electric vehicles, which it perceives to be the critical barrier to the wide-spread deployment of electric vehicles. Through its two first rounds of solicitations, ARPA-E has funded a series of projects targeting battery technologies (Table 6).

In its first solicitation in 2009, the agency awarded $151 million to 37 energy research projects. Of these, 4 projects dedicated to the advancement of energy storage technology for motive applications received more than $16.5 million. In its second solicitation in 2010, the agency awarded $106 million in funding to 37 projects focusing specifically on three technological areas: electrofuels, batteries for electric vehicles and carbon capture. Of these 37, 10 projects with a total of $34.6 million in funding were under the Batteries for Electrical Energy Storage in Transportation (BEEST) program, targeting battery development for electric vehicles.

All of the projects funded by ARPA-E aim to produce the next generation of batteries for hybrid and electric vehicles by increasing energy and power density and reducing cost manyfold.

Recipient	**Technology**	**Funding**
Broad Funding Announcement (First Solicitation)		
FastCap Systems	Low Cost, High Energy and Power Density, Nanotube-Enhanced Ultracapacitors	$5,349,932
Arizona State University	Sustainable, High-Energy Density, Low-Cost Electrochemical Energy Storage - Metal-Air Ionic Liquid (MAIL) Batteries	$5,133,150
Envia Systems	High Energy Density Lithium Batteries	$4,000,000
Inorganic Specialists	Silicon Coated Nanofiber Paper as a Lithium-Ion Anode	$1,999,447
Batteries for Electrical Energy Storage in Transportation (Second Solicitation)		
ReVolt Technology LLC	Zinc Flow Air Battery (ZFAB), the Next Generation Energy Storage for Transportation	$5,000,335
Sion Power Corporation	Development of High Energy Lithium-Sulfur Cells for Electric Vehicle Applications	$5,000,000
PolyPlus Battery Company	Development Of Ultra-high Specific Energy Rechargeable Lithium-Air Batteries Based On Protected Lithium Metal Electrodes	$4,996,311
Massachusetts Institute of Technology	Semi-Solid Rechargeable Power Sources- Flexible, High Performance Storage for Vehicles at Ultra-Low Cost	$4,973,724
Applied Materials	Novel High Energy Density Lithium-Ion Cell Designs via Innovative Manufacturing Process Modules for Cathode and Integrated Separator	$4,373,990
Planar Energy Devices	Solid-State All Inorganic Rechargeable Lithium Batteries	$4,025,373
Pellion Technologies	Low-Cost Rechargeable Magnesium Batteries with High Energy Density	$3,204,080
Recapping Inc.	High Energy Density Capacitors	$1,000,000
Stanford University	The All-Electron Battery- a quantum leap forward in energy storage	$1,000,000
Missouri University of Science & Technology	High Performance Cathodes for Lithium-Air Batteries	$999,997

Table 6: Batteries for Electrical Energy Storage in Transportation. Source: (ARPA-E 2010)

Market pull

Aside from supporting research and creating competitive environments for industry players, government can also play a role in encouraging a market for hybrid and electric vehicles and accelerating consumer adoption through regulatory policies and fiscal incentives such as subsidies for clean vehicles. Alternatively, the government may also contribute to market growth by driving initial demand through government procurement.

Regulatory Standards

Governments worldwide are progressively tightening emission and fuel efficiency standards for motor vehicles. In the United States, the state of California has led the way in emission constraints since 1990 with the Zero Emission Vehicle Program. The program mandated by the California Air Resources Board[13] (CARB) originally required that in 1998, 2% of the vehicles produced for sale in California had to be zero emission vehicles[14] (ZEV), increasing to 5% in 2001 and 10% in 2003. The mandate was then modified in 1996 by eliminating the requirements for the intermediate years, but keeping the 10% ZEV target for 2003 and allowing partial ZEV (PZEV) credits for extremely clean vehicles that are not necessarily pure ZEV's. The ZEV program was amended once again in 2001, after recognizing constraints due to cost, lead-time, and technical challenges (CARB 2004). The modifications allowed large manufacturers to meet their ZEV requirement with a mix of vehicles: 6% of the vehicles produced for sale in California are Partial Zero Emission Vehicles[15] (PZEV's), or 2% are Advanced Technology PZEV's[16] (AT PZEV's) or 2% are pure ZEV's. In 2002, General Motors, DaimlerChrylser and several California car dealers filed a federal lawsuit against the California Air Resources Board (CARB) alleging the new ZEV rules violate a federal law barring states from regulating fuel economy in any way. The federal district judge issued a preliminary injunction that prohibited the CARB from enforcing the 2001 ZEV

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[13] California is the only state that is permitted to have such a regulatory agency, since it is the only state that had one before the passage of the federal Clean Air Act. Other states are permitted to follow the ARB standards, or use the federal ones, but not set their own.

[14] A zero-emissions vehicle, or ZEV, is a vehicle that emits no tailpipe pollutants from the onboard source of power.

[15] These vehicles meet the most stringent tailpipe emission standards and come with a 15 year / 150,000 mile emissions warranty.

[16] These vehicles have extremely low (PZEV) emission levels and also employ ZEV-enabling technologies such as electric drive.

amendments to the sale of new vehicles in model years 2003 or 2004. The CARB made further changes to the ZEV program in 2003. It reset the percentage requirements for model year 2005, revised the way ZEV credits were calculated and offered more than one path for automakers to meet the specified requirements.

In 2009, the Federal EPA, responsible for managing emissions standards, declared that it would largely adopt California's standards on greenhouse gas emissions. The regulations required vehicle makers to meet "corporate average fuel economy“ (CAFE) standards of 35 miles per gallon by 2020. The Obama administration more recently announced a new national fuel economy and emissions policy, requiring an average mileage standard of 39 miles per gallon for cars and 30 miles per gallon for trucks by 2016, compared to the current average of 25 miles per gallon for all vehicles. The administration is also on policies that would lead to further improvements for the 2017-2025 timeframe.

Meeting these tough regulations will undoubtedly drive the electrification of vehicle propulsion systems.

Tax Credits

The U.S. federal government is also offering a subsidy that aims to reduce the cost gap between electric vehicles and gasoline-powered cars, featured in the Energy Improvement and Extension Act of 2008 as part of the Emergency Economic Stabilization Act of 2008. The legislation provides tax credits of $2,500 plus $417 for each kWh of battery capacity over 4 kWh, up to $7,500 for cars under 10,000 pounds, $10,000 for larger vehicles under 14,000 pounds, $12,500 for bigger trucks under 26,000 pounds, or $15,000 for larger trucks and equipment. The credits will begin to be phased out two calendar quarters after cumulative sales of qualified vehicles reach 250,000 vehicles. The credit will be reduced by 50% in the first two calendar quarters of the phaseout period and by another 25% in the third and fourth calendar quarters. The credit is scheduled to be eliminated after December 31, 2014, regardless of how many qualifying vehicles have been sold.

The credit aims to incentivize first adopters and drive volumes of electric vehicles. As volumes increase, economies of scale emerge, allowing cost reductions and efficiencies that would decrease the cost gap between electric vehicles and conventional combustion vehicles.

Government Procurement

With the government operating more than 1 million vehicles, by acting as a first adopter and converting a portion of its fleet to hybrid or electric vehicles, it has the ability to contribute to the market growth of electric vehicles. As high production volumes are reached, both battery manufacturers and automakers can benefit from economies of scale and achieve cost reductions.

Until recently, American lithium-ion battery companies, which consist mostly of startups, have had their batteries manufactured in Asia. Building a manufacturing facility requires significant capital resources which these companies have been reluctant to allocate without a guaranteed customer base. Conversely, the lack of domestic manufacturing capacity has been a bottleneck for automakers in the US (Jenkins 2009). Without a steady supply of lithium-ion batteries, the most critical component in an electric vehicle, automakers are hesitant to invest in capital-intensive electric vehicle platforms, especially given that market demand has not been established yet.

Both the United States federal and state governments have taken active measures to break the status quo and accelerate the development of manufacturing capacity for batteries and electric drive components as well as the deployment of electric drive vehicles to help establish American leadership in developing the next generation of advanced vehicles.

What About China?

The United States is not the only country pushing for the electrification of vehicles and seeking leadership in the industry. China has emerged as a serious contender with years of manufacturing expertise, alluring cost-cutting opportunities, and aggressive government support.

Chinese leaders are aiming to turn the country into one of the leading producers of hybrid and all-electric vehicles by 2015. Their motives for entering the industry are to reduce urban pollution and decrease oil dependence in addition to creating thousands of jobs and boosting exports. They have set a goal of raising annual production capacity to 500,000 hybrid or all-electric cars and buses by the end of 2011, compared to the estimated 1.1 million hybrid or all-electric light vehicles for Japan and South Korea and 267,000 for the United States (Bradsher 2009). To incentivize drivers to adopt these technologies, China is planning to offer subsidies of up to $8,800 per vehicle to taxi fleets and local government agencies in 13 Chinese cities (Bradsher 2009). The state electricity grid has already been ordered to install charging stations in Beijing, Shanghai and Tianjin. Another interagency panel is planning tax credits for adopters of alternative energy vehicles. However, this still might not be enough to close the cost gap. When Tianjin-Qingyuan Electric Vehicle Company puts its all-electric Saibao midsize sedan on sale this year; the body will come from a sedan that normally sells for $14,600. When equipped with a gasoline engine and a $14,000 battery pack and electric motor, the retail price will nearly double to almost $30,000 (Bradsher 2009). Even if the government delivers on the subsidies promised, the car will remain considerably more expensive than its gasoline-powered counterpart.

It seems that Western industries are not the only ones suffering from high cost. Even with government support and subsidies, Asian manufacturers are still encountering hardships in overcoming what remains a critical barrier, cost.

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Section 6 – Conclusion

Vehicle electrification has emerged as a viable strategy for addressing many of the world's energy challenges, including energy security, climate change and soaring demand. However, as history has shown, electric vehicles cannot compete effectively with their gasoline counterparts if they are not able to provide comparable functionality at the same or lower cost. The battery component will have a major role in enabling these conditions as it ultimately defines the cost, range and safety of these vehicles.

The fate of the electric vehicle industry hinges not only on a single player, but on an entire ecosystem that includes automakers, battery manufacturers, policy makers and consumers.

Automakers are seeing their supply chain transform dramatically. Engines, gearboxes, and exhaust systems are being replaced by batteries and electric motors. Cars such as the Tesla Roadster and the Nissan Leaf are more akin to electronic products than traditional vehicles. As logistics and supply chains in the automotive industry are transformed, different models of supply chain relations are emerging. Some automakers are developing battery packs in-house in vertically integrated organizations, others have forged partnerships with battery suppliers, while still others have completely outsourced the development and manufacturing of the battery pack to an external supplier. No model is optimal for all manufacturers. Startup automakers have different capabilities than mainstream manufacturers. First-movers operate in different conditions than market-followers. Despite these differences, the technological challenges remain the same: develop a battery pack with higher energy capacity and power rating while reducing cost and ensuring safety. In the short-term, knowledge of cell characteristics will be key to the competitiveness of automakers, as is the pack integration into the vehicle which relies greatly on software. As the battery industry evolves and technological challenges are addressed, supply chain relations are likely to evolve as well. While standardization of the battery pack is unlikely, battery technology will mature and automakers will need to find new ways to establish their competitive edge. At that point, innovation in software for battery management is likely to play a major role.

Meanwhile, most automakers remain reluctant to make significant investments in electric vehicles without assurances that battery makers have the technology and are ready for large scale production. Battery makers for their part are looking at an industry that is still in its embryonic stages and are trying to adequately position themselves. Giants in the battery industry such as Panasonic and Johnson Controls are making strategic acquisitions and joint ventures to establish themselves. Startups such as A123 Systems still need to prove themselves to a risk-averse industry, while Chinese manufacturers such as BYD can achieve significant cost reductions but still need to improve their quality standards before being recognized as a major player. With currently 98% of global production located in Asia, American and European battery makers will have a hard time gaining market share.

Market evolution by itself will likely take too long to achieve deployment at large scale. Governments worldwide are stepping up to accelerate the development of battery technology and the manufacturing capabilities required to launch an electric vehicle industry. Asian countries such as Japan, China and South Korea are capitalizing their mature battery industries to develop electric vehicles, while the United States is investing billions of dollars to jumpstart its battery and electric vehicle industries. The government has several mechanisms to achieve this. It can work on the supply-side, by investing in basic research and development or by supporting companies in developing manufacturing capabilities. Alternatively, it can focus on the demand-side, either through regulatory standards or consumer incentives. There is broad consensus on one point: the role of the government is not to pick winners and losers, but rather to create a level playing field for players to compete. While this is agreed upon in principle, one wonders whether it is being followed in practice.

Cost remains the critical barrier to entry, and therefore governments such as the United States and China are offering subsidies to consumers to narrow the cost gap between electric and motor vehicles. Targeting consumers is key, especially given that the vehicle is the second most important possession for the great majority of Americans (Manufacturers 2003). With market appeal remaining uncertain, incentivizing the average consumer to adopt electric vehicles will help drive demand towards the higher volumes that will ultimately enable cost reductions. A trend that is likely to emerge for electric vehicles is market segmentation. Some vehicles (more specifically batteries) will be designed for high power and performance while others will be designed for longer range, utility, and lower cost. This differentiation will allow automakers to tailor their vehicles to the specific needs of their customers in hopes of accelerating adoption.

Future Work

This thesis has touched on many issues that would be interesting to pursue further. As mentioned earlier in the conclusion, the lithium-ion battery industry consists of an ecosystem of various players, each having its own opportunities and constraints.

The geographic distribution of battery manufacturers is fairly imbalanced. Asian manufacturers located in Japan, China and South Korea dominate the market with more than 98% market share, which is largely attributable to the consumer electronics industry. As electric vehicles grow in popularity, the United States is looking to jumpstart its battery industry to avoid shifting from an addiction to foreign oil to an addiction to imported lithium-ion cells. One question that is yet to be answered is whether the United States is capable of developing a sustainable lithium-ion battery industry that can compete with Asian manufacturers. This question touches on many separate issues. First, from an economic standpoint, can American manufacturers be cost-competitive? A detailed study of the industry cost structure in both the United States and Asian countries (Japan, China and Korea) would be needed to answer this question. Second, how relevant are the knowledge and expertise acquired in the consumer electronics industry to electric vehicles? Is this knowledge transferable? To what extent does it influence the competitiveness of Asian manufacturers? A third issue is the importance of geographic location. Is co-location with automakers as important in the electric vehicle industry as it has been in the consumer electronics industry? This question touches on the modularity of the battery pack discussed in Chapter 4.

Automakers are heading into unchartered territory. As electric vehicles emerge, logistics and supply chains will focus less on traditional drivetrains and more on battery and electronics. How comparable are the logistics and supply chains of consumer electronics to those of electric vehicles? If any similarities are identified, can one draw any lessons that would be applicable to the electric vehicle industry?

Another major player in the industry is the government. While this thesis has described the different mechanisms available to influence the industry, it does not address the effects of such measures. Which are the most efficient and effective channels to allocate government resources? The economic repercussions and technological outcomes of each mechanism need to be analyzed.

Finally, the importance of the consumer has been established earlier. Studies of consumer behavior and adoption with regard to electric vehicle could diminish market uncertainties and facilitate industry projections.

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