A Global Analysis and Market Strategy in the Electric Vehicle Battery Industry

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Abstract

As use of electric vehicles has been expected to grow, the batteries for the electric vehicles have become critical because the batteries are a key part of the paradigm shift in the automotive industry. However, the demand for electric vehicles has been growing slowly and the electric vehicle battery industry still has internal and external competitions to become a standardized energy source for electric vehicles. The electric vehicle batteries will need to improve their performance, safety, life cycle, charging time and infrastructure to succeed in the market.

Since the electric vehicle battery industry is associated with a variety of stakeholders, it should enhance its performance in complex internal and external competitions by cooperating closely with them. Automobile makers in particular are becoming competitors as well as clients to the electric vehicle battery industry. As automobile makers aggressively invest in electric vehicle battery manufacturing, the internal competitions to achieve technology, cost, and market leadership are accelerating. In addition, automobile makers have developed fuel cell technologies for fuel cell electric vehicles. Since the fuel cell has the advantages in electric driving ranges, in charging time, and in vehicle design, the fuel cell electric vehicles could well restructure the entire electric vehicle market if they reduce fuel prices and establish charging infrastructures.

The electric vehicle battery industry should seek to speed technology advances for the next generation of battery technologies by identifying key materials, improve battery performance, enhance manufacturing capabilities, and reduce manufacturing costs by expanding the scope of its R&D. If it needs strategic partnerships, the electric vehicle battery industry should look for long-term strategic partners with whom it can grow together. Moreover, the electric vehicle battery industry should enhance its value chain by interacting with suppliers at all tiers from raw material companies to final product makers. Furthermore, the electric vehicle battery industry should seek to attain the economies of scale for the cost and market leadership by diversifying the batteries' applications. Finally, it should compete not on price but on value while strengthening the industry's power.

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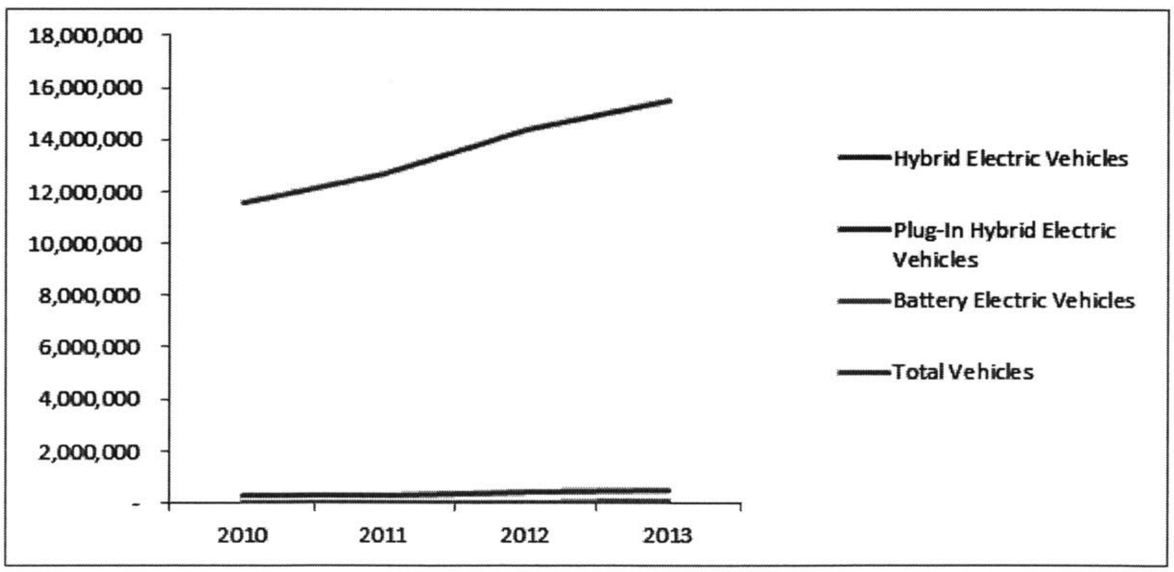
Chapter 1: Introduction

1.1. Motivation

When General Motors launched EV1, the first mass-produced battery electric vehicle, in 1996, the automotive industry realized that it must not invest in mass production of electric vehicles until low battery capabilities and limited driving ranges were going to be enhanced [1]. However, when Toyota Motor Corporation launched the Prius, the first commercial hybrid electric vehicle, in 1997 in Japan, it suggested an alternative way to approach the mass market for electric vehicles. Since the success of the Prius, the electric vehicle has been regarded as the ultimate vehicle to protect the environment and solve natural resource depletion problems [2]. About 20 years later, the electric vehicle is still considered as a next-generation car and is not popularized yet.

Although the electric vehicle market has been gradually growing, it is still too tiny to impact the overall automotive market and environment. According to electric vehicle sales data in the U.S. from Electric Drive Transportation Association, electric vehicle sales in the U.S. accounted for a 3.8% market share in 2013 on a sales unit basis. While the sales number of electric vehicles in the U.S. in 2013 doubled from 274,000 cars in 2010 to 592,000 in 2013, the hybrid electric vehicle led growth of the electric vehicle market and the battery electric vehicle has not become popular yet [3].

Figure 1: Electric Vehicle Sales in the U.S. (Unit)



Source: Electric Drive Transportation Association, 2014

The electric vehicle will shift the paradigm of automotive industry from internal combustion engines to batteries. As battery becomes the most important part in automotive manufacturing, battery capability will become the most critical part in automotive sales because it replaces the function of internal combustion engine. Thus, electric vehicle battery manufacturing takes the most influential role in electric vehicle industry and market.

I would like to analyze the electric vehicle market from an electric vehicle battery manufacturer's point of view and develop its market strategy in the industry. In addition, I would like to consider how growing electric vehicle battery industry affects consumer market to boost the current sluggish electric vehicle sales.

1.2. Methodology

The electric vehicle industry and market are very complicated to understand and predict because many stakeholders are involved from consumers to governments, policies, and infrastructures to technology competitions and generate complexity beyond the system dynamics. Thus, I use a system dynamics model to analyze the electric vehicle industry and market and discover the main driving forces. And then, I develop the market strategy to grow the electric vehicle market as an electric vehicle battery manufacturer.

In the introduction, I explain the electric vehicle history and categorize the electric vehicle types. I also include impacts of battery technologies on the electric vehicle history and battery differences of each electric vehicle type in this section.

Secondly, I analyze the electric vehicle industry and market with a system dynamics model. I draw a causal loop diagram to understand system dynamic patterns in the electric vehicle industry and market. Based on the causal loop diagram, I also find out how the main driving forces affect this whole industry and market and then, I discover which factor battery manufacturers should focus on to grow the market.

Thirdly, I compare the competition for the electric vehicle battery technology. The analysis of the competition to achieve the technology standard will help develop R&D and business portfolios of battery manufacturers for the following section.

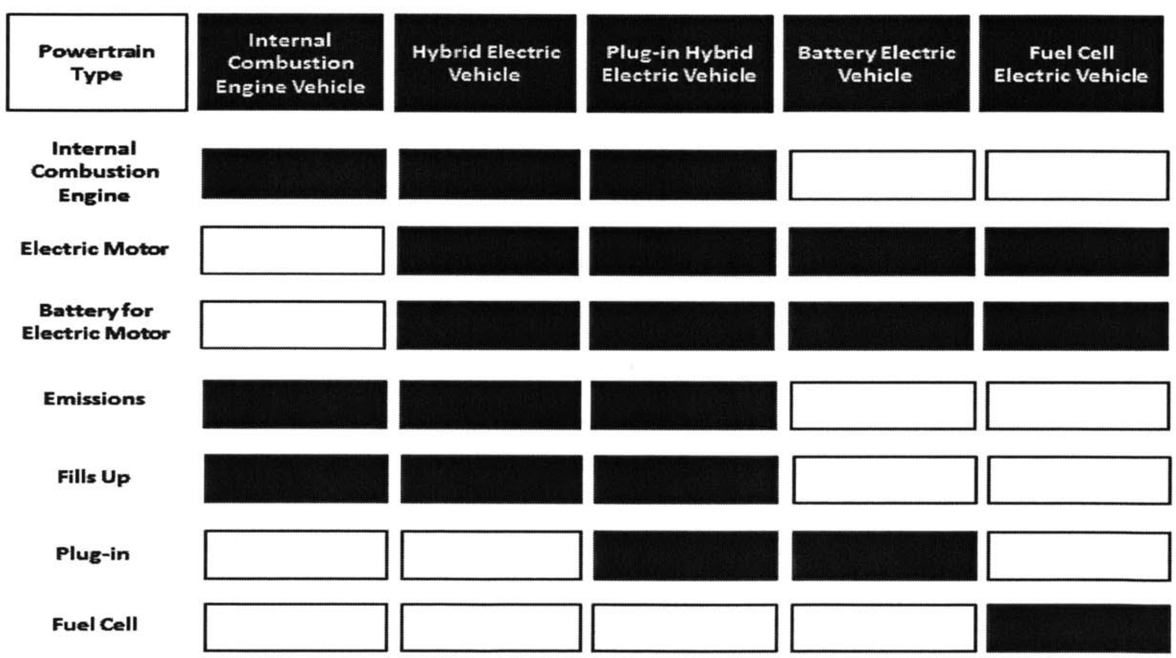
Lastly, I analyze the current strategies of battery manufacturers and develop a market strategy for them to boost the entire industry and market. I find out how battery manufacturers strengthen their value chains and interact with stakeholders to grow the electric vehicle market.

1.3. History of Electric Vehicle

Since Richard Trevithick, a Cornish mine manager, developed the first motor vehicle based on a steam powered engine in 1801, automobiles experienced technology competitions for commercialization because the steam powered engine did not provide advanced performance compared to horse-driven transport. In 1834, Thomas Davenport, an American blacksmith and inventor, developed the first current electric motor and applied it to locomotives. And then, non-rechargeable battery-powered electric vehicles were invented but the non-rechargeable battery restricted commercialization of electric vehicles. After the first rechargeable lead-acid battery was invented by Gaston Plante, a French physicist in 1865, several automobile companies such as Baker Electric, Oldsmobile and Studebaker produced battery electric vehicles in the late 1800s in the U.S. History of electric vehicles started half a century ahead of history of internal combustion engine vehicles because the first internal combustion engine vehicles were conceived in 1885 [4].

However, underdeveloped battery technology hampered the early success of electric vehicles at the beginning of the 20th century. Because the electric vehicles were only appropriate for driving on paved roads, they were constrained to urban usage. At the beginning of the 20th century, while the U.S. started to construct paved roads, Europe did not. Hence, electric vehicles were not able to succeed in the global automotive market. In addition, the huge success of Henry Ford's Model T enabled internal combustion engine technology to capture the lead in the standardized technology competition in automobile manufacturing. After the electric vehicle lost attractiveness against internal combustion engine, the electric vehicle disappeared from the commercial market until GM launched EV1 and Toyota launched Prius.

Figure 2: Electric Vehicle Comparison Chart [5]



The electric vehicles are broadly categorized as battery powered electric vehicles and fuel cell electric vehicles, based on the power source type. The battery powered electric vehicles can be subdivided as hybrid electric vehicles, plug-in hybrid electric vehicles, and battery electric vehicles according to powertrain type. Compared to the internal combustion engine vehicle, the electric vehicle can be supplied several components: electric motor, battery for electric motor, plug-in, and fuel cell. The level of independence from the internal combustion engine is a main factor to decide the level of the electric vehicle.

Battery characteristics vary in the electric vehicle types since the level of independence of internal combustion engine determines how much battery capacity and capability are needed. The hybrid electric vehicle and plug-in hybrid electric vehicle require less battery capacity compared to the battery electric vehicle. The battery capacity of the battery electric vehicle is 30 to 60 times that of the hybrid electric vehicle and 1 to 7 times that of the plug-in hybrid electric vehicle [6]. Electric vehicle battery manufacturing will be dramatically boosted by the growth of the battery electric vehicle market which needs higher capacity of battery. Thus, electric vehicle battery manufacturers are contemplating how to raise the battery electric vehicle market as well as the hybrid electric vehicle market and plug-in hybrid electric vehicle.

Table 1: Battery Characteristics of Electric Vehicle: typical battery performance for the near term (medium car) (Nemry, Francoise, et al., 2009)

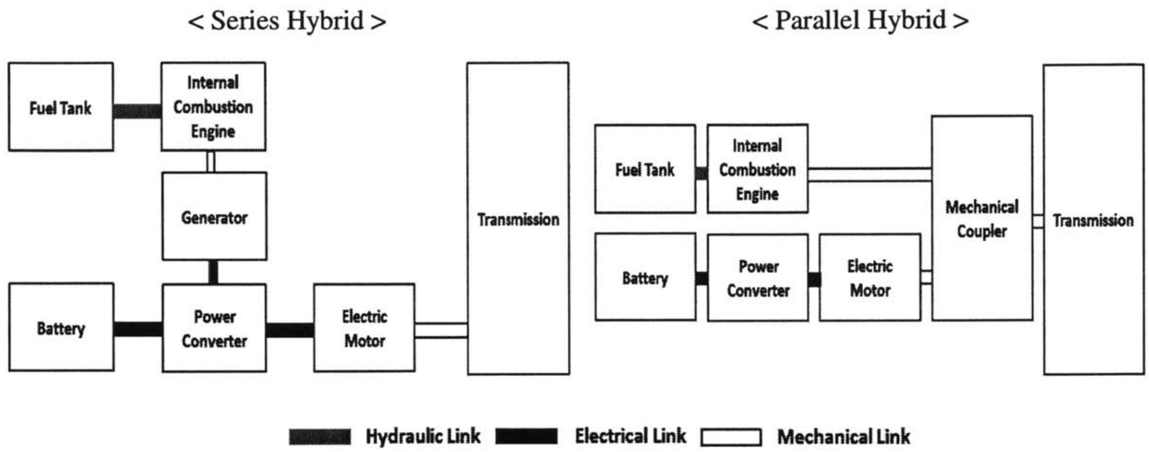
	Hybrid Electric Vehicle	Plug-in Hybrid Electric Vehicle	Battery Electric Vehicle
All Electric Range (mile)	0	10 ~ 60	150 ~ 200
Total Capacity (kWh)	1.3	4 ~ 30	30 ~ 60
Specific Energy (Wh/kg)	46	110 ~ 160	110 ~ 160
Energy Density (Wh/l)	200 ~350	400 ~ 600	400 ~ 600
Battery Pack Weight (kg)	29	70 ~ 190	300 ~ 500

1.3.1. Hybrid Electric Vehicle

Although the electric vehicle is more competitive in high-energy efficiency and zero environmental pollution than the internal combustion engine vehicle, it has disadvantages such as low operation range per battery charge because of lower energy density of the batteries [7]. This was the critical reason why electric vehicle lost the initiative in the earlier competition with the internal combustion engine vehicle at the beginning of the 20^{st} century.

The hybrid electric vehicle compensates for the disadvantages of the electric vehicle's low performance by changing propelling modes. The hybrid electric vehicle is designed to connect engine and electric propelling parts. The way of linking two parts is largely distinguished between series and parallel hybrids (Figure 3). The hybrid electric vehicle is operated in the pure engine-propelling mode when the battery is completely exhausted and the internal combustion engine does not have power to charge the battery, or the internal combustion engine is able to supply enough power with the battery fully charged. The hybrid electric vehicle is operated in the pure electric-propelling mode when it drives at very low speed or in areas where carbon dioxide emissions are strictly restricted. When the hybrid electric vehicle needs greater power, both the engine and the electric motor function. In addition, the battery is charged in one of two ways. The battery is charged by regenerative braking, in which is the kinetic energy of the vehicle is converted to electric energy through the electric motor and then is stored in the battery. Alternatively, the battery is charged by the engine while the vehicle is at a standstill.

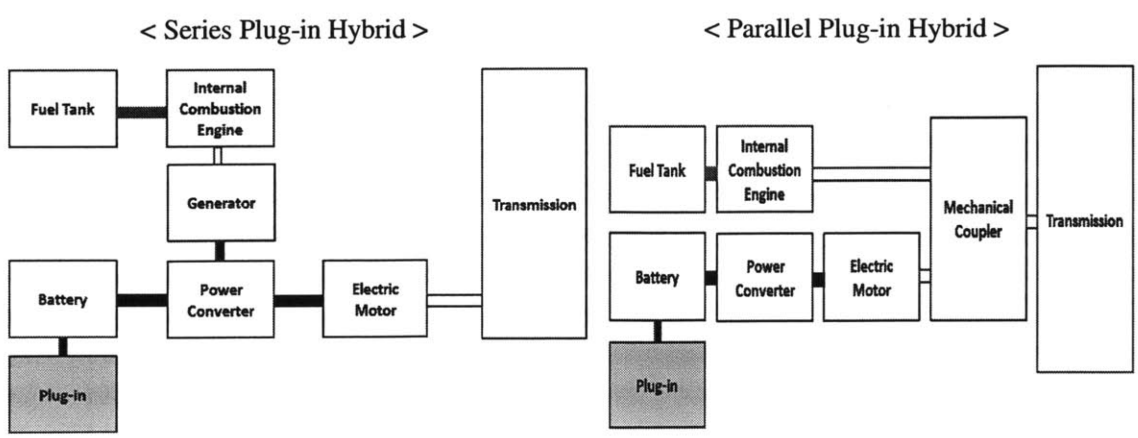
Figure 3: Hybrid Electric Vehicle Structure (Ehsani, Mehrdad, et al., 2010)



1.3.2. Plug-in Electric Vehicle

Although both the hybrid electric vehicle and the plug-in electric vehicle combine an engine-propelling part and an electric-propelling part, the plug-in electric vehicle is distinctive in three aspects: chargeability by an external electric power source through a plug, size of battery packs, and all-electric range [8]. The plug-in electric vehicle is able to be charged with plug and has larger battery packs than the hybrid electric vehicle. Because the battery pack size depends on the battery capability, the plug-in electric vehicle is equipped with a higher capability of the battery packs than the hybrid electric vehicle. This higher capability of the battery packs allows the plug-in electric vehicle to drive with only electric power. If the plug-in electric vehicle is not charged with outside electric power, its basic performance principle and fuel consumption are the same as those of the hybrid electric vehicle. Finally, the plug-in electric vehicle is able to drive in the electric mode if it is fully charged and the drive distance is shorter than its all-electric range.

Figure 4: Plug-in Hybrid Electric Vehicle Structure [9]



1.3.3. Battery Electric Vehicle

The battery electric vehicle uses only electrical energy to drive. It is charged by plugging in external electric power source. Since the battery electric vehicle does not use fossil fuel, it does not produce carbon dioxide emissions and does not have a tailpipe. Even though charging batteries with electricity involves fossil fuel and carbon dioxide emissions, the U.S. Environmental Protection Agency categorizes the battery electric vehicle as a zero-emission vehicle. However, lacking any backup by an internal combustion engine means that the battery electric vehicle cannot operate when the battery cannot be recharged in time and the battery power becomes completely depleted.

The first mass-produced battery electric vehicle was EV1, produced by GM in 1996. GM launched EV1 using a lead-acid battery [1], but the lead-acid battery increased the vehicle volume, weight, and price because of its low energy density. Even though GM changed the lead-acid battery to a nickel-metal-hydride battery for EV1, it failed to win a mass market because of low battery capabilities and the limited electric driving range [10].

Figure 5: Battery Electric Vehicle Structure [11]

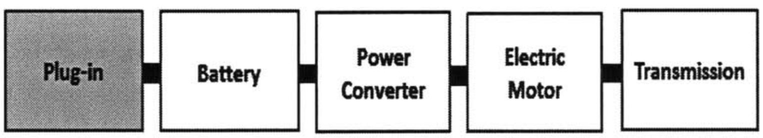


Table 2: Battery Specifications of 2014 Electric Vehicles

	Type	EPA car class	Battery Type	Energy Storage	All-Electric Driving Range	Full Charge
Tesla Model S [12]	BEV	Large	Li-ion	60 kWh	208 miles	1 hour
BMW i3 [13]	BEV	Compact	Li-ion	18.8 kWh	80 ~ 100 miles	3 to 6 hours
Chevrolet Spark [14]	BEV	Compact	Li-ion	21 kWh	82 miles	7 hours
Chevrolet Volt [14]	PHEV	Mid-size	Li-ion	16.5 kWh	38 miles	4 hours
Nissan Leaf S [15]	BEV	Mid-size	Li-ion	24 kWh	84 miles	4 hours
Toyota Prius Plug-in [16]	PHEV	Mid-size	Li-ion	4.4 kWh	11 miles	1.5 hours
Toyota Prius [16]	HEV	Mid-size	Ni-MH	1.3 kWh	1 mile	N/A
Ford Focus Electric [17]	BEV	Large	Li-ion	23 kWh	76 miles	3.6 hours
Honda Fit EV [18]	BEV	Mid-size	Li-ion	20 kWh	82 miles	3 hours
Smart for Two Electric [19]	BEV	Two-seaters	Li-ion	17.6 kWh	68 miles	6 hours

※ EPA car class: The United States Environmental Protection Agency (EPA) has developed a classification scheme used to compare fuel economy among similar vehicles. Passenger vehicles are classified based on a vehicle's total interior passenger and cargo volumes.

Thus, the battery capability and charging electricity are the main factors for the battery electric vehicle to become popular. The energy storage of the battery determines all-electric driving range, the driving distance in the only-electric mode. The current energy storages of commercial battery electric vehicles are around 20 kWh and all-electric driving ranges are less than100 miles except for the battery electric vehicles of Tesla in 2014 (Table 2). The U.S. Department of Transportation's Federal Highway Administration states that 100 miles covers more than 90% of the U.S. household vehicle trips [8]. According to the 2009 National Household Travel Survey in the U.S., the average vehicle trip length was 9.7 miles for all purposes, 12.2 miles for the purpose of commuting to work and 11.2 miles for social and recreational purposes [20]. In addition, charging time limits freedom of vehicle trips. The current full charging time of commercial battery electric vehicles ranges from 3 to 7 hours except the battery electric vehicles of Tesla in 2014 (Table 2). Also, paucity of public charging stations impedes the growth of the electric vehicle market. Even though the U.S. and Japan are the leading electric vehicle markets in the world [21], the number of public electric charging stations, including both fast and regular charging, is insufficient even in the U.S. and Japan. In the U.S., 8,024 public electric stations are available in 2014 [22] and in Japan, 4,700 public electric stations are available in 2013 [23].

1.3.4. Fuel Cell Electric Vehicle

Since GM developed the first fuel cell electric vehicle, Chevrolet Electrovan, in 1966, the automotive industry has invested in commercializing fuel cell electric vehicles [122]. GM tried to develop technologies to enhance fuel cell electric vehicles, and in 2002, introduced an innovative vehicle design, which is called a "skateboard" platform with its AUTOnomy concept car. The "skateboard" chassis is suited for efficiently loading fuel cells and an electric powertrain, and inexpensively adding different body types [123]. It demonstrates that that a new technology can lead to an innovative design. It can be applied to battery electric vehicles, and one of the success factors of Tesla is its own design of battery pack and electric powertrain on a skateboard.

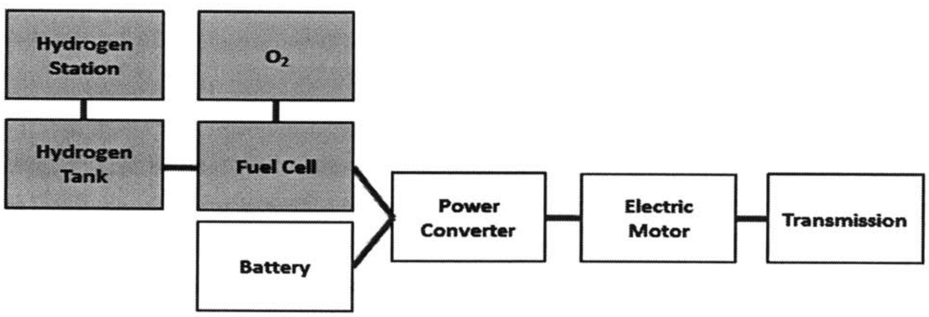
In 2013, automobile makers announced inter-corporate collaboration on patents and research on fuel cell electric vehicle technologies. These automobile makers released "concept cars" of the fuel cell electric vehicle at worldwide motor shows and announced time frames to launch mass-produced fuel cell electric vehicles from 2015 to 2017 to 2020 (Table 3). The automobile makers are strongly convinced that the fuel cell electric vehicle will become the next generation of technology to realize zero emission mobility by compensating for the weaknesses of the battery electric vehicle in the future.

The fuel cell electric vehicle is equipped with a fuel cell system based on the battery electric vehicle structure. While the battery electric vehicle stores electricity by charging from external electricity sources, the fuel cell electric vehicle generates electricity through the electrochemical reaction between hydrogen fuel and antioxidant chemical energy [28]. Although the fuel cell electric vehicle needs a battery to enhance power density for starting, its battery energy storage is much lower than the battery electric vehicle. A 2 kWh battery is supplied Toyota's fuel cell electric vehicle concept car which was unveiled at 2014 CES [29].

Table 3: Target to Launch Fuel Cell Electric Vehicle and Partnership among Automobile makers

	Target to Launch	Partnership
Toyota Motor	2015	Toyota and BMW: collaboration of the research into hydrogen fuel cell powertrains [24]
BMW	N/A	
Honda	2015	Honda and GM: collaboration on fuel cell technology [25]
GM	2020	
Nissan-Renault	2017	Nissan-Renault, Daimler and Ford: joint development of common fuel cell system [26]
Daimler AG		
Ford Motor		
Hyundai-Kia	2015	No partnership [27]

Figure 6: Fuel Cell Electric Vehicle Structure [30]



The fuel cell electric vehicle is superior to the battery electric vehicle in several respects: less vehicle weight, higher energy density, longer all-electric driving range, zero emissions and short refueling time [31]. However, the fuel cell electric vehicle will not become popular until it overcomes several obstacles: safety problems, expensive vehicle price and tremendous costs to build hydrogen refueling infrastructures [32].

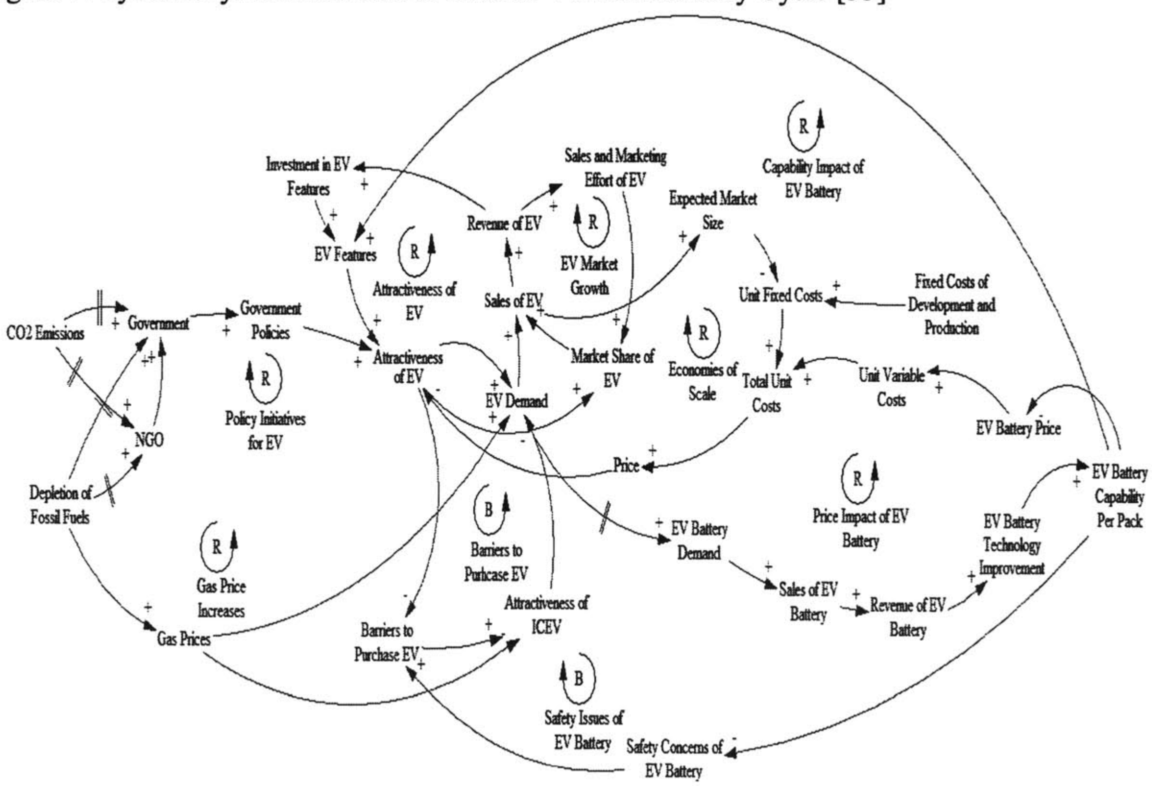
Chapter 2: System Dynamics

System dynamics is an approach to analyze behaviors in complex systems. The *causal loop diagram* is a system dynamic method which maps out the entire system with the variables and their interactions. The *causal loop diagram* helps visualize how different variables in a system are interrelated. In the *causal loop diagram,* a link marked "positive" indicates that two variables change in the same direction and a link marked "negative" indicates that two variables change in the opposite direction. The positive feedback loops are termed *reinforcing l*oops and the negative feedback loops are termed *balancing loops* [33].

2.1. System Dynamics of the Electric Vehicle

The *causal loop diagram* of the electric vehicle industry cycle attempts to capture the complex interactions among variables and their impact on associated variables (Figure 7). In this *causal loop diagram,* the electric vehicle industry cycle is reinforced by gas price increase, policy initiatives for the electric vehicle, attractiveness of the electric vehicle, the electric vehicle market growth, economies of scale and price and capability impacts of the electric vehicle battery; The electric vehicle industry cycle is balanced by barriers of the electric vehicle and safety issues of the electric vehicle battery.

Figure 7: System Dynamics Model of Electric Vehicle Industry Cycle [33]



2.1.1. Reinforcing Loop

2.1.1.1. Gas Price Increase

The "Gas Price Increase" *reinforcing loop* accounts for how depletion of fossil fuels increases the price of gas and then the gas price increase stimulates the electric vehicle demand. The electric vehicle demand reinforce through the gas price increase loop as fossil fuels are depleted and oil prices increase.

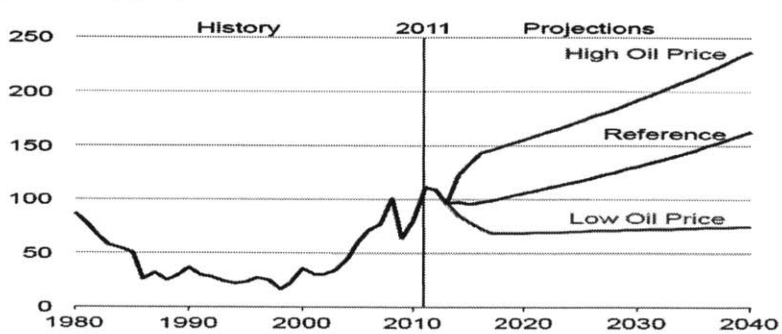
According to the simulation of the gas price impact on the hybrid electric vehicle, the gas price increase boosts its sales and the gas price decrease reduces its sales (Beresteanu and Li, 2006). Under the condition of the 1999 gas price at $ 1.55, Beresteanu and Li simulated the change of the hybrid electric vehicle sales from 2001 to 2006. Its sales in 2006 decreased by 14.02% as a result of the gas price dropping from $ 2.62 to $ 1.55, while its sales in 2002 increased by 3.88% as the gas price rose from $ 1.54 to $ 1.55.

Table 4: Total Hybrid Sales in the 22 Metropolitan Statistical Areas Under the 1999 Gas Price [34]

Year	Gas Price in 2006 ($)	Price Difference from 1999	Hybrid Sales in 22 MSAs	New Sales	Decrease in Sales	Decrease in Sales in %
2001	1.75	0.21	5,461	4,888	573	10.49
2002	1.54	-0.01	8,231	8,551	-320	-3.88
2003	1.76	0.23	9,117	8,813	304	3.33
2004	2.01	0.48	17,732	15,586	2,146	12.10
2005	2.41	0.88	43,658	39,757	3,901	8.94
2006	2.62	1.07	50,059	50,776	8,283	14.02

The U.S. Energy Information Administration forecast that the Brent spot oil price will increase to $163 per barrel in 2040 based on 2011 dollars in the reference scenario and increase to $237 in 2040 per barrel in the high oil price scenario, while it declines to $75 per barrel in 2040 in the low oil price scenario [35]. The scenarios of oil price increase reinforce the electric vehicle demand.

Figure 8: Average Annual Brent Spot Crude Oil Prices in Three Cases, 1980-2040 (2011 dollars per barrel) [35]



2.1.1.2. Policy Initiatives for Electric Vehicle

The "Policy Initiatives for Electric Vehicle" *reinforcing loop* explains how CO_2 emissions increase and the depletion of fossil fuels awaken governments to the seriousness of environmental problems and resource scarcity, and increasing concerns of the governments are converted to policy initiatives such as incentives for electric vehicle purchasing, charging infrastructure installations, R&D investments and regulations of CO_2 emissions. As the policy initiatives increase, the attractiveness of the electric vehicle increases. This occurs because the incentives for electric vehicle purchasing enable customers to purchase them at a competitive price, and more infrastructure to charge the electric vehicle or swap its batteries will allow electric vehicle users to have more freedom to travel without charging concerns. The R&D subsidies of the governments stimulate the electric vehicle industry to develop cutting-edge technologies, and the electric vehicle produces little or no CO_2 emissions by consuming little or no fossil fuel. Eventually, the electric vehicle demand is reinforced through the government policies as the attractiveness of the electric vehicle raises the electric vehicle demand.

Each government has taken policy initiative by providing incentives for the electric vehicle purchase, charging and battery swapping infrastructure installations, R&D investments and regulation of CO_2 emissions. The U.S. offers a tax credit to the electric vehicle customers, up to $ 7,500, while China and Japan offer purchase subsidies. Regarding charging infrastructure installations, the U.S. also provides a tax credit for both commercial and residential purposes, while Japan and France sponsor half the price of the electric vehicle charging infrastructure. In addition, each country allocates a budget for funding electric vehicle R&D and the U.S. is budgeting $ 675 m in 2014 for technologies including batteries, fuel cells, infrastructures and vehicle systems [21]. Furthermore, in the regulation of CO_2 emissions, the U.S. Environmental Protection Agency implemented the renewable fuel standard program in 2010 and, if it is fully implemented by 2022, the U.S. can reduce tailpipe emissions of CO_2 by 138 m metric tons [36]. The EU aims to reduce CO_2 emissions from 2009 to 2020 by 40% and if the goal is fully reached by 2020, the EU can reduce tailpipe emissions of CO_2 by 7 m metric tons. The EU will fine automobile makers for non-compliance with the legal target [37].

Table 5: Government Policies to Promote Electric Vehicles [21]

Type	Policy details	Applied Countries
Financial	Subsidies for the electric vehicle purchase	China, India, Italy, Japan, Spain, Sweden etc.
	Tax benefit in vehicle registration or circulation	Denmark, France, Germany, Netherlands etc.
	Subsidies for the installation of the charging infrastructure	Denmark, Finland, France, Germany, India, Japan, Netherlands, Spain, U.K., U.S. etc.
	Subsidies for R&D	China, Denmark, France, Germany, India, Japan, Netherlands, Spain, Sweden, U.K., U.S. etc.
Non-Financial	CO_2 regulation and legal target	U.S., EU etc.

2.1.1.3. Attractiveness of Electric Vehicle

The "Attractiveness of Electric Vehicle" *reinforcing loop* shows how the electric vehicle demand increases the attractiveness. A demand increase of the electric vehicle results in a sales increase of the electric vehicle, which leads to revenue increase of the electric vehicle for investment in additional electric vehicle features. Thus, the enhancement of the electric vehicle features by the investments heightens the attractiveness of the electric vehicle, and the electric vehicle demand reinforces the attractiveness of the electric vehicle through the positive feedback loop. The "Attractiveness of Electric Vehicle" *reinforcing loop* creates a virtuous cycle.

2.1.1.4. Electric Vehicle Market Growth

The "Electric Vehicle Market Growth" *reinforcing loop* describes how the sales increase of the electric vehicle causes the revenue increase of the electric vehicle, which leads to more sales and marketing efforts of the electric vehicle, and the augmented efforts increase the market share of the electric vehicle which generates the sales increase of the electric vehicle. The sales of the electric vehicle reinforce the market share of the electric vehicle through the "Electric Vehicle Market Growth" *reinforcing loop.*

2.1.1.5. Economies of Scale

The "Economies of Scale" *reinforcing loop* clarifies how the attractiveness of the electric vehicle achieves economies of scale in manufacturing of the electric vehicle. The more attractive the electric vehicle is, the greater the electric vehicle demand is. The increase of the electric vehicle demand raises the sales of the electric vehicle, which expands the expected market size. If the market size is expected to expand, that contributes to reducing the unit fixed costs, which consist of total unit costs. The total unit cost decrease causes a price decrease which leads an attractiveness increase of the electric vehicle. The attractiveness of the electric vehicle reinforces the cost reduction and the competitive price through the "Economies of Scale" *reinforcing loop.*

2.1.1.6. Price Impact of Electric Vehicle Battery

The "Price Impact of Electric Vehicle Battery" *reinforcing loop* explains how growing electric vehicle demand enhances the electric vehicle battery capability and price, which leads to more competitive total unit costs and greater attractiveness of the electric vehicle. The more the electric vehicle demand is, the more the electric vehicle demand tends to become. The demand increase for the electric vehicle results in more sales of the electric vehicle battery which lead to more revenues for the electric vehicle battery. In turn, more revenues of the electric vehicle battery cause more electric vehicle battery technology improvements which increase the battery capabilities per pack and decrease the price of the battery. The price decrease of the electric vehicle battery reduces unit variable costs and total unit costs which relate to the price of the electric vehicle. Then, the price decrease of the electric vehicle increases the electric vehicle demand. The price impact of the electric vehicle battery on the electric vehicle reinforces the electric vehicle demand through the *positive feedback loop.*

According to the battery capacity estimation of F. Nemry et al. in 2009 and the lithium-ion battery cost estimation of Anderman in 2010, the cost burdens of the battery are estimated to range from $3,600 to $36,600 for the plug-in hybrid electric vehicle and from $ 15,000 to $42,000 for the electric vehicles in 2015. Although actual prices of the electric vehicle battery are kept confidential and vary according to energy capacity and design, the CRS Report for Congress estimated that the electric vehicle battery prices would be between $8,000 and $18,000 [38]. According to a report of the U.S. Department of Energy in 2012, the lithium-ion battery price of the Chevrolet Volt was around $8,000 (16 kWh), 20% of its Manufacturer's Suggested Retail Price (MSRP) and the lithium-ion battery price of the Nissan Leaf was around $12,000 (24 kWh), 32% of its MSRP. The lithium-ion battery price of the Tesla Model S was around $35,000 (60kWh), 61% of its MSRP [39]. Since the battery electric vehicle requires greater battery capacity, the price impact of the battery on the electric vehicle is greater than on the hybrid electric vehicle or the plug-in hybrid electric vehicle.

Table 6: Lithium-Ion Battery Cost Estimates [6] [40]

Type	Timeframe	Battery Capacity	Cost/kWh	Battery Cost
Plug-in hybrid electric vehicles	2015	4 ~ 30kWh	$900-1,220/kWh	$3,600-36,600
	2018-2020		$675-900/kWh	$2,700-27,000
Electric vehicles	2015	30 ~ 60kWh	$500-700/kWh	$15,000-42,000
	2018-2020		$375-500/kWh	$11,250-30,000

Table 7: Lithium-Ion Battery Cost in 2012 [39]

	Type	EPA Car Class	Energy Storage	MSRP	Battery Cost	Ratio of Battery Cost
Chevrolet Volt	PHEV	Mid-size	16 kWh	$39,145	$8,000	20%
Nissan Leaf	BEV	Mid-size	24 kWh	$37,250	$12,000	32%
Tesla Model S	BEV	Large	60 kWh	$57,400	$35,000	61%

2.1.1.7. Capability Impact of Electric Vehicle Battery

The "Capability Impact of Electric Vehicle Battery" *reinforcing loop* articulates how enhancement of the electric vehicle battery capability per pack improves the electric vehicle features and demand, which contribute to the electric vehicle battery demand. The increasing electric vehicle battery capability per pack strengthens the electric vehicle features by offering higher energy storage and longer all-electric driving range. The better the electric vehicle features are, the more the attractiveness of the electric vehicle is. The growing attractiveness of the electric vehicle raises the electric vehicle demand, which leads to the electric vehicle battery demand, sales and revenues. The revenue increase of the electric vehicle battery allows the technology improvement of the electric vehicle battery and its improvement enlarges its capability per pack. The capability of the electric vehicle battery per pack is reinforced through the positive feedback of the "Capability Impact of Electric Vehicle Battery" loop.

2.1.2. Balancing Loop

2.1.2.1. Barriers to Purchase Electric Vehicle

The "Barriers of Electric Vehicle" *balancing loop* accounts for how the barriers to purchase the electric vehicle decrease the electric vehicle demand. The less attractive the electric vehicle is, the higher the barrier to purchase the electric vehicle is. The electric vehicle remains less attractive in its limited all-electric driving range, its less affordable price of the electric vehicle, and its insufficient charging infrastructure [6]. The barriers to purchasing of the electric vehicle make consumers feel more attracted to the internal combustion engine vehicle, and that greater attractiveness lowers the electric vehicle demand. The lesser attractiveness of the electric vehicle balances the electric vehicle demand through its negative feedback.

2.1.2.2. Safety Issues of Electric Vehicle Battery

The "Safety Issues of Electric Vehicle Battery" *balancing loop* explains how growing safety concerns of the electric vehicle battery expand barriers to purchase the electric vehicle and decrease the electric vehicle demand. The more the barriers to purchase the electric vehicle are, the more attractive the internal combustion engine vehicle is. Its increasing attractiveness reduces the electric vehicle demand, which generates less electric vehicle battery demand, sales and revenues. Less revenue for the electric vehicle battery retards its improvement which sets back its capability per pack.

Safety concerns remain regarding electric vehicles simply because they adopt electrically powered vehicle technologies although their safety standards and designs have been enhanced. Fires and potential risks of the electric vehicles with lithium-ion batteries have been reported several times. Tesla stated that the collision of a Tesla Model S with a large metallic fragment caused the fire which started from its lithium-ion battery in 2013 [41]. A Chevrolet Volt caught fire at a National Highway Traffic Safety Administration testing center of the U.S. in 2011 three weeks after a crash impact test, although National Highway Traffic Safety Administration (NHTSA) and GM determined that the Chevrolet Volt was not more risky than conventional gasoline engine vehicles [42]. In addition, the fire in a UPS Boeing 747 which was loaded with lithium-ion batteries occurred in 2010. Operating out of the range of a specific voltage and temperature accelerates degradation of lithium-ion batteries, and the possibility of catching fire grows in that situation [43]. Charging beyond the voltage limit results in overheating, which will trigger the electrolyte to become volatile and cause chemical decomposition [44]. Further, overdischarging can lead the copper current collector to melt down because of internal short circuits [45]. Also, piercing by steel can cause fire by generating a chemical reaction in lithium-ion batteries [46].

On the other hand, the fuel cell electric vehicle has associated safety issues in refueling, on-board fuel storage and operation since it uses the fuel cell on top of the electrically powered vehicle technologies. Because hydrogen is a relatively small molecule, gaseous hydrogen readily leaks and the fuel cell electric vehicle is exposed while refueling to potential problems with the electric circuitry near the flammable hydrogen gases. In turn, hydrogen fires have distinctive properties such as flames invisible in daylight, and no soot or smoke, and rapid burning [47]. The hard-to-detect characteristics of hydrogen fires can increase the potential danger of fire in fuel cell electric vehicles which use batteries for additional electricity [48].

2.2. Key Considerations for Battery Manufacturers of Electric Vehicle

2.2.1. The electric vehicle industry is sensitive to external factors.

The electric vehicle industry interacts not only with internal factors of its value chains but also with external factors such as CO_2 emissions and depletion of fossil fuels. These external factors push governments and NGOs to generate government policies which are favorable to the electric vehicle industry. The battery manufacturers of the electric vehicle should actively consider the external factors when developing its strategies.

2.2.2. Greater battery capability for the electric vehicle is critical to increase the attractiveness of the electric vehicle.

Since the battery capability for the electric vehicle is a key factor to enhance features, improve safety and achieve competitive pricing, the battery manufacturers must continue investing in R&D for battery technology enhancement. They need to improve current battery and manufacturing technologies and discover next-generation battery technologies in order to gain an advantage in battery technology competition.

On the other hand, since the battery capability of the electric vehicle is closely related to the attractiveness of the electric vehicle, automobile makers need strategic partnerships with the battery manufacturers in order to have stable and reliable battery supplies. Also, the long lead time to develop and launch new vehicles encourages automobile makers to require a long-term dedicated relationship to the battery manufacturers. Therefore, the battery manufacturers need to build strong strategic partnerships with automobile makers based on superior battery technologies and manufacturing capabilities.

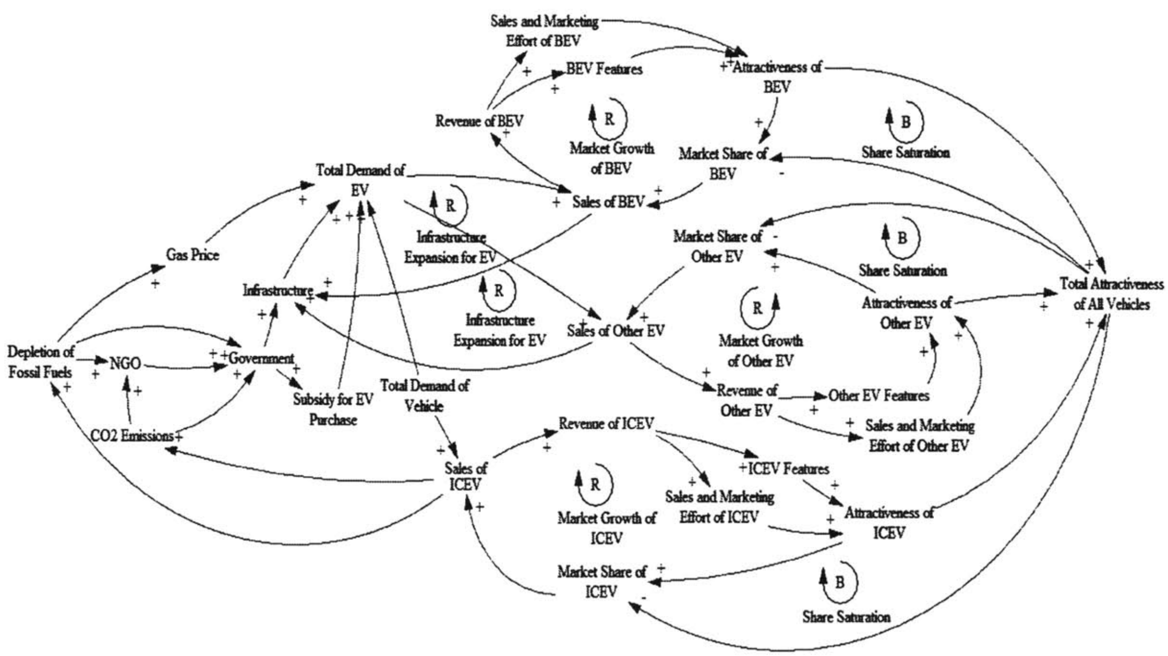
2.2.3. The automotive industry can compensate for lower electric vehicle sales with additional sales of internal combustion engine vehicles.

Except for some specialized electric vehicle companies, most automobile makers have full vehicle line-ups from the internal combustion engine vehicle to the electric vehicle. Thus, the automotive industry can compensate for lower electric vehicle sales with additional sales of the internal combustion engine vehicle, since barriers to purchasing the electric vehicle prompt customers to consider the internal combustion engine vehicle.

2.2.4. The electric vehicle industry is eager to power the electric vehicle with the most advanced energy source, whether it is a type of battery or a fuel cell.

Batteries for the electric vehicles are very important factors directly affecting their features, safety issues and prices. However, the electric vehicle industry is interested in adopting the most advanced energy source which is environmentally friendly, highly energy-efficient, safe and easy to mass-produce, whether a type of battery or a fuel cell. That is why the electric vehicle industry is co-developing the fuel cell electric vehicle for commercialization as well as the hybrid electric vehicle, the plug-in hybrid electric vehicle and the battery electric vehicle at the same time. Thus, battery manufacturers of the electric vehicle should consider not only which battery technology will win in the battery technology competition but also which electric vehicle type will win in the electric vehicle technology competition.

Figure 9: System Dynamics Model of Vehicle Competitions [33]



2.2.5. The electric vehicle industry needs the cooperation of stakeholders.

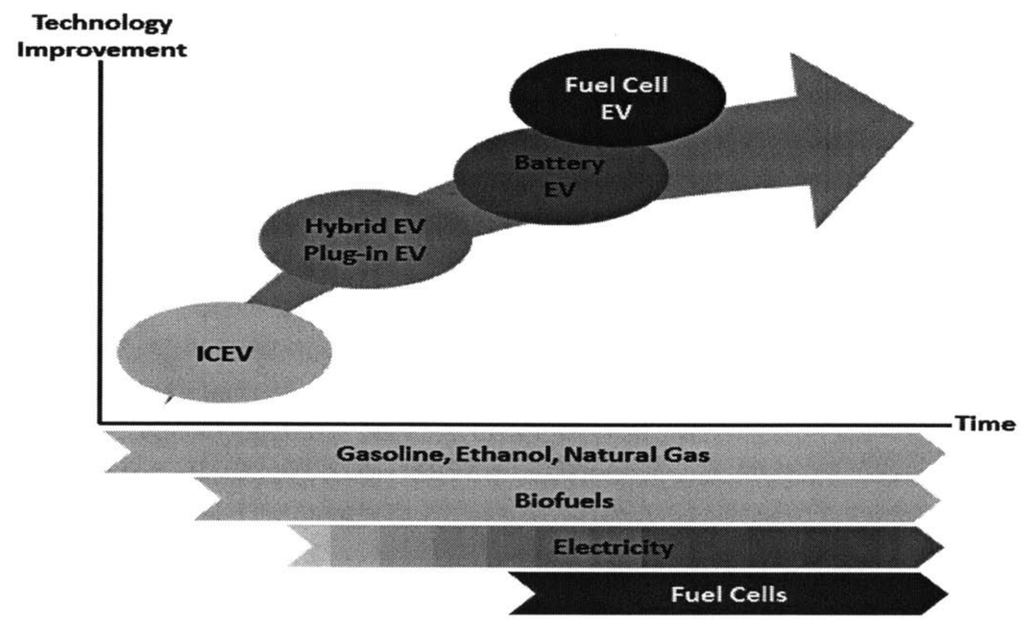
The electric vehicle industry needs the cooperation of stakeholders to expand the infrastructures of charging or battery swapping. Rapid expansion for the infrastructures requires enormous investment, technology standardization of charging modes and plug types, and collaboration of the electric vehicle industry [120]. Even though Better Place tried to establish a business of battery charging and swapping beyond automobile makers, only Renault agreed to a battery swapping service for limited models with Better Place, and Better Place went bankrupt in 2013 [121]. Tesla is concerned about battery swapping only for itself, but the dedicated service will not contribute to improving the whole electric vehicle industry.

Chapter 3: Batteries of Electric Vehicles

3.1. Analysis of Energy Sources of Electric Vehicles

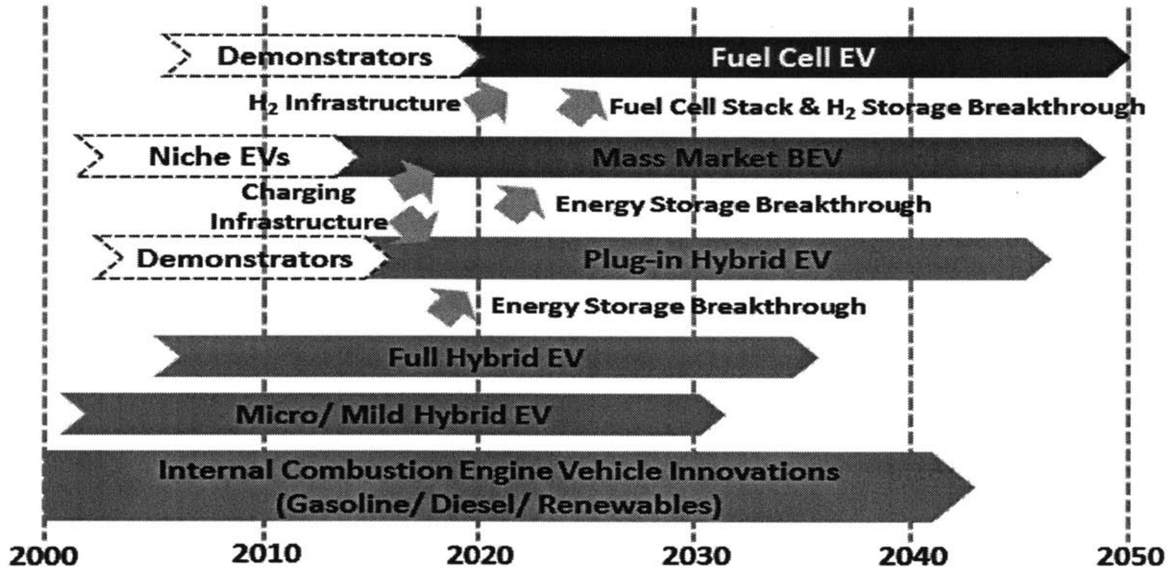
Although energy sources of the Electric Vehicle are diverse, - from batteries, fuel cells, capacitors and flywheels to solar – Chau et al. (1998) projected that batteries will become the main energy sources for the electric vehicle because of the technology maturity and economies of the scale [49]. In turn, the fuel cell has been identified as the next major energy source for the electric vehicle, according to the vision of future transportation of the National Renewable Energy Laboratory (NREL). In the technology roadmap of the electric vehicle with energy source (Figure 10), vehicle fuel economy and emission reduction is ranked in the order of the fuel cell electric vehicle, the battery electric vehicle, plug-in electric vehicle, the hybrid electric vehicle and the internal combustion engine vehicle. In addition, the U.K. government predicted that the technology of the fuel cell electric vehicle would be mature for mass market in 2009 [50].

Figure 10: Technology Roadmap of the Electric Vehicle with Energy Sources [51], [52]



Major automobile makers such as GM, Toyota and Hyundai have announced technology partnerships with competitors to advance fuel cell electric vehicle launches. While the first hybrid electric vehicle was only launched in 1997, a full century after the internal combustion engine vehicle began proliferating, the new fuel cell type of the electric vehicle will follow the hybrid electric vehicle or the battery electric vehicle. The major automobile makers have forecast that they will launch the fuel cell electric vehicles by 2020. While battery manufacturers have enhanced energy density, power, life cycle and cost reduction of batteries in battery technology competitions, fuel cell and other potential technologies have been developed mainly by automobile makers. Before the battery electric vehicles become popular in the mass market, the automobile makers plan to launch the next technology products in the near future; consequently, battery manufacturers should consider the fuel cells not as a next technology but as a competing technology. In this section, I will analyze and compare battery technologies and draw out key considerations for the battery manufacturers of the electric vehicle.

Figure 11: Technology Roadmap for the UK's Decarbonization of Road Transport [50]



3.1.1. Batteries of Electric Vehicles

Regardless of electric vehicle types, lithium-ion batteries have become popular to adapt because of the technology maturity. The growth of lithium-ion battery demands for digital gadgets such as tablet PCs and smartphones has accelerated the technology's maturity and price reduction. Although Toyota Prius and Lexus Hybrid Electric Vehicles are still using nickel-metal hydride batteries, major battery technology in the electric vehicle industry is lithium-ion battery (Table 8). Toyota also considers changing Prius' battery from nickel-metal hydride to lithium-ion [53].

However, the competition for the electric vehicle battery technology does not end with lithium-ion battery technology. Lexus intends to keep using nickel-metal hydride batteries even though most major automobile makers are adapting or planning to adapt only lithium-ion batteries to their vehicles. In a recent press interview, Mark Templin, executive vice president of Lexus International, stated that Lexus will continue using nickel-metal hydride batteries and wait while the next generation of battery technology for the electric vehicle as it concentrates on enhancing its hybrid electric vehicle technology [54]. In turn, lithium-ion battery is subcategorized according to the choice of cathode such as lithium manganese oxide spinel, lithium iron phosphate and lithium cobalt oxide. Therefore, it is important to analyze and compare battery technologies and their potential enhancement.

Table 8: Battery Overview Adapted to the Electric Vehicle

Automobile Makers	Vehicle	Vehicle Type	Battery Type [55]	Battery Manufacturer
Tesla	Model S	BEV	Lithium-ion (NCA) [56]	Panasonic
GM	Chevrolet Volt	PHEV	Lithium-ion (LMO) [57]	LG Chem
	Chevrolet Spark	BEV		
Toyota	Prius	HEV	Nickel-metal hydride	Primearth [58]
	Prius Plug-in	PHEV	Lithium-ion (NCA)	Panasonic
Lexus	CT/ ES/ GS/ LS/ RX	HEV	Nickel-metal hydride	Primearth
BMW	Active 3/5/7	HEV	Lithium-ion (NMC)	Johnson Controls [59]
	i3	BEV	Lithium-ion (NMC)	Samsung SDI
Nissan	Pathfinder	HEV	Lithium-ion	Hitachi
	Leaf S	BEV	Lithium-ion (LMO)	AESC
Honda	Accord	HEV/BEV	Lithium-ion (LMO-NMC/ Hard Carbon)	Blue Energy [60]
	Fit EV	BEV	Lithium-ion (LTO)	Toshiba
Hyundai	Sonata	HEV	Lithium-ion (LMO)	LG Chem
BYD	e6	BEV	Lithium-ion (LFP)	BYD [61]
Daimler Benz	E400/ S400	HEV	Lithium-ion (NCA)	Johnson Controls [62]
Mitsubishi	I-MiEV	BEV	Lithium-ion (LTO)	Toshiba
	Outlander	PHEV	Lithium-ion (LMO) [63]	Lithium Energy Japan
Ford	Fusion/ C-Max	HEV/ PHEV	Lithium-ion (NCA)	Panasonic
	Focus Electric	BEV	Lithium-ion (LMO)	LG Chem

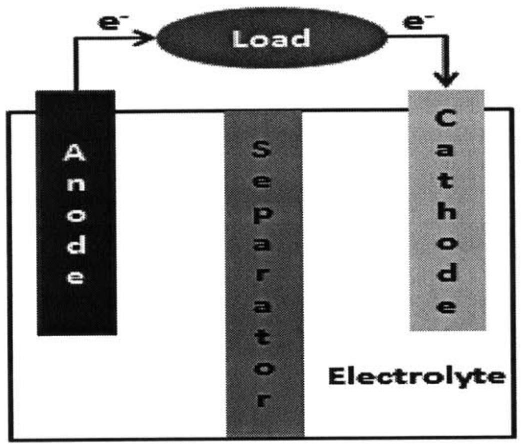
※ Primearth: a joint venture of Toyota and Panasonic

※ Blue Energy: a joint venture of Honda and GS Yuasa

3.1.1.1. Battery Structure

The batteries for electric vehicles in this thesis are restricted to secondary batteries which are rechargeable. The secondary batteries are comprised of chemical materials that enable the batteries to reverse discharge when the batteries are supplied with charging current. After a battery is discharged by consuming its energy, it restores energy through the charging process. Charge and discharge activities occur within the battery life expectancy. As batteries are largely composed of battery cells and packs, battery cells technically consist of anodes, cathodes and electrolytes. Oxidation occurs in the anodes, and electrons that come out of the anode flow to the external electrical circuit. Reduction occurs in the cathodes, and the electrons from the external electrical circuit flow back to the cathodes. In the charging process of the secondary batteries, the electron flow is reversed. The electrolytes serve as an ionic conductor of electricity. They enable the electrodes to keep flowing or chemical reactions of anodes and cathodes to continue occurring. In this process, the chemical energy of a battery is converted to the electrical energy. The separators take a role in separating the anodes and the cathodes so that shorting is prevented, and the chemical reactions of the anodes and the cathodes are parted. The battery performance can vary depending on chemical materials used for battery cells [64].

Figure 12: Electrochemical Structure of Battery Cell [64]



3.1.1.2. Lead-Acid

A lead-acid battery has more than 100 year history since it was introduced for commercial purpose in the electric vehicle in 1865 and has been widely applied to various products. It is very popular to use for starting, lighting, and ignition batteries (SLI batteries) in either internal combustion engine vehicles or electric vehicles. The lead-acid battery contains a metallic lead for the anode, a lead dioxide for the cathode, and a sulfuric acid electrolyte. Even though it has the oldest history among battery technologies and is a mature technology offering the most competitive price, the lead-acid battery is least competitive for the electric vehicle battery use because it has the lowest specific energy and energy density when compared to competing battery technologies [65]. In 1996, GM produced EV1, the first mass-produced battery electric vehicle, which used a 533kg lead-acid battery for its main energy source with 70 miles of all-electric driving range [1]. However, the lowest energy density of the lead-acid battery requires a massive volume and heavy weight for long distance of all-electric driving range, and the price of the lead-acid battery rises according to its volume and weight increase. As a result, automobile makers started to find a more suitable battery technology for mass production of the electric vehicles. In 1997, Toyota launched Prius, the first commercial hybrid electric vehicle with nickel-metal hydride battery [66]. Although GM changed the battery for EV1 to nickel-metal hydride battery in 1999 [10], EV1 failed to attract a mass market, and automobile makers (including GM) deferred plans to target the mass market with battery electric vehicles.

The lead-acid batteries have still been evolving for the electric vehicles. Advanced lead-acid battery technologies, including ultrabattery consisting of the lead-acid battery and asymmetric supercapacitor, have been represented for a low cost option for hybrid electric vehicles. A study of advanced lead-acid batteries shows that they are competitive because they need lower safety controlling costs than lithium-ion batteries, and more than 90% of the lead can be profitably recycled. This study also introduced the Effpower project which converted a nickel-metal hydride battery into an advanced lead-acid battery and showed the possibility of solving weight and volume issues [67]. However, it is hard to predict future utilization of advanced lead-acid battery technologies for electric vehicles because they are reconsidered as an alternative for micro and mild hybrid electric vehicles, and other competing battery technologies have been actively being developed.

3.1.1.3. Nickel-Metal Hydride

A nickel-metal hydride battery consists of nickel hydroxide for the anode and hydrogen for the cathode [64]. Nickel-metal hydride batteries became popular for the early hybrid electric vehicles because of their greater energy density, lighter weight, and smaller volume than lead-acid batteries [38]. Starting with the introduction of Toyota's Prius with a nickel-metal hydride battery in 1997, however, as shown at table 8, most batteries for the electric vehicles have been replaced by lithium-ion batteries which have higher specific energy and greater energy density than nickel-metal hydride batteries. While Toyota announced in 2009 that Prius would keep using nickel-metal hydride batteries after feasibility tests of alternative battery technologies, a recent press release showed that Toyota is considering switching to lithium-ion batteries [53].

One reason why most companies have replaced nickel-metal hydride batteries to lithium-ion batteries is the corporate dynamics in which nickel-metal hydride battery technology was involved. GM bought up a controlling interest of Ovonics, which invented the large format of nickel-metal hydride battery technology in 1994, and Texaco acquired GM's stake of GM Ovonics in 2001. At the same year, Chevron merged with Texaco, and in 2004, Texaco Ovonic Battery Systems was changed to Cobasys [68], which was a joint venture of Chevron and Energy Conversion Devices Ovonics, with each having a 50% stake [69]. Chevron had veto power over sales and licensing of nickel-metal hydride batteries and the right to seize the intellectual property rights of Cobasys [70]. Cobasys maintained a strict sales policy which would only accept large orders of batteries, more than 10,000 units [71], and kept patents of nickel-metal hydride battery technologies exclusive, with no licensing. Automobile makers and other nickel-metal hydride battery companies had to develop their own battery technologies by avoiding Cobasys's patents. While this sales policy and exclusive patents limited improvement of nickel-metal hydride battery technologies, lithium-ion battery technologies have been enhanced by overcoming weaknesses in safety concerns, cost, and life cycles.

3.1.1.4. ZEBRA (Sodium-Nickel-Chloride)

The ZEBRA (Zero Emissions Batteries Research Activity) is based on sodium-nickel-chloride chemistry. Its positive electrode is mainly made of nickel-chloride and its negative electrode is made of sodium. The sodium ions form the liquid sodium negative electrode by moving through a beta alumina tube. It is superior to nickel-metal hydride and competitive with lithium-ion in producing energy, and it is powerful enough to perform at extremely cold and hot temperatures [38]. Although ZEBRA batteries were used for initial battery electric vehicle models of THINK and Smart, they have been replaced by lithium-ion batteries because of higher specific power and energy density and faster charging speed. Furthermore, ZEBRA batteries have a critical inherent weakness: They need to be maintained at an internal operating temperature of between 270°C and 350°C in order to keep their metal-salt electrolyte in liquid state [72]. Because ZEBRA batteries need to be kept at this high temperature even when not in operation, they cause extra energy loss, produce additional CO_2 emissions, and raise safety concerns [73].

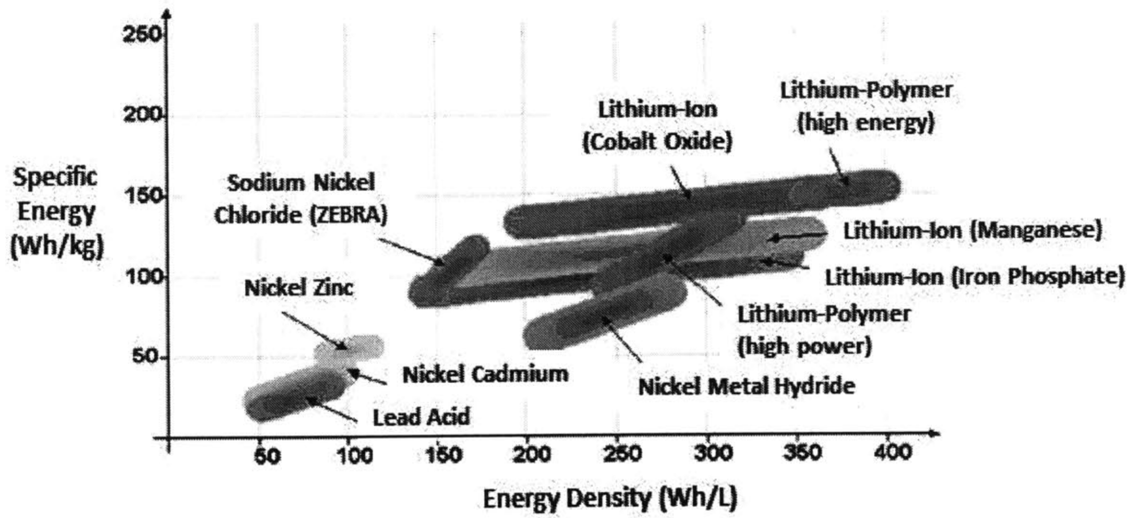
Although sodium-based batteries have higher theoretical energy density than lithium-ion batteries, their practical energy density is lower [74]. The practical energy can be enhanced by R&D investment and new battery technology introductions but ZEBRA battery studies are not currently in active development.

3.1.1.5. Lithium-Ion

Since lithium is the lightest among metals and electrochemicals, a lithium-ion battery can have high energy and power density. Lithium-ion batteries consist of lithium metal-based materials for the cathode and carbon (graphite) for the anode. The performances of lithium-ion batteries depend on materials of the cathode and anode, and there are a number of possible lithium-ion battery combinations. The representative cathode materials in lithium-ion batteries are lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium iron phosphate (LFP), lithium nickel cobalt aluminum oxide (NCA), and lithium nickel manganese cobalt oxide (NMC).

Since the 1990s, LCO batteries have been prominently used for portable batteries of consumer electronics because of their high energy and power density, and Tesla first adopted LCO batteries for an electric vehicle in a series car in 2008. However, increasing price and safety issues of LCO made lithium-ion battery manufacturers find alternative cathode materials such as LMO, LFP, NCA and NMC [75]. LMO batteries are cost-competitive because of using manganese, but have the disadvantage of low life expectancy because manganese dissolves in the electrolyte. LMO batteries were first used for an electric vehicle by Mitsubishi Motors in 2009. LFP batteries have advantages in power density, life expectancy, and safety, but they have low energy density. While other lithium-based battery technologies needed at least 10 years to be adopted for electric vehicles after the first commercialization of rechargeable cells, LFP batteries were first used for an electric vehicle by MODEC in 2007 [73]. NCA and NMC batteries have relatively higher energy density but have weaknesses in price and safety since they consist of cobalt. On the other hand, lithium titanate oxide (LTO) is a new anode material which has advantages in power, safety, life cycle and charging time, although carbon remains the most common material for the anode of lithium based batteries. However, LTO-based batteries have lower voltage and energy density compared with other lithium-ion batteries [76].

Figure 13: Specific Energy and Energy Density of Batteries [77]



While lithium-ion battery manufacturers are putting efforts into enhancing power density and energy density and reducing manufacturing costs, numerous studies to look for next generation batteries such as metal air and lithium sulfur are being conducted. Metal air batteries are comprised of pure metals for the anode while using air for the cathode. The energy densities of metal air batteries are decided by the anode materials – lithium, sodium, aluminum, zinc and silicon, and the lithium air battery theoretically performs with the highest specific energy including oxygen weight. The practical energy density of the lithium air battery, considering efficiency from battery to wheels in the electric vehicle, is comparable with the practical energy density of gasoline. Because the current practical specific energy of gasoline is 2,244 Wh/kg, and the current energy efficiency of the lithium-ion battery to wheels in the electric vehicle is 50% while the specific energy of lithium air battery is 5,200 Wh/kg. Most research of lithium air batteries are based on non-aqueous lithium air because lithium metal should be protected water and CO_2 by the liquid electrolyte. A stable electrolyte for the lithium air batteries need to be identified because its discharge products are sensitive to electrolyte materials and it is limited to reversible cycling. In addition, there is a need to develop a way to supply purified oxygen for the lithium air battery cathodes. Although it is the best way to supply highly purified O_2 from a tank, the tank reduces the energy density and specific energy of the lithium air batteries.

Zinc air, aluminum air and silicon air batteries have been studied only as primary batteries. Overall, metal air batteries need to develop rechargeability as secondary batteries with high energy density and specific energy [55].

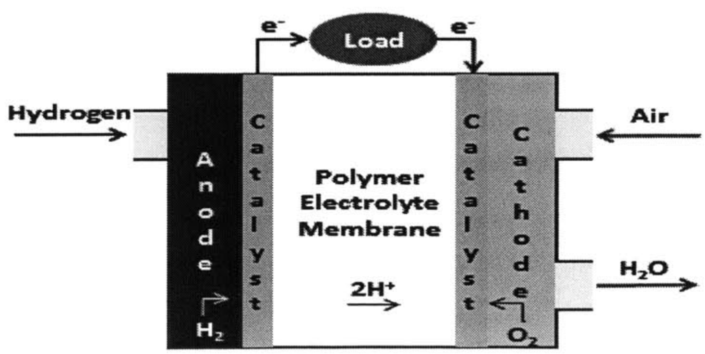
On the other hand, a lithium sulfur battery uses sulfur as a cathode because sulfur is light, plentiful and environmentally friendly. It has a theoretical specific energy of 2,500 Wh/kg and an energy density of 2,800 Wh/L. However, a lithium sulfur battery also needs to overcome obstacles which sulfur intrinsically has: its limitation of electrical conductivity and the high solubility of polysulfide compounds, with resulting in large volume change during the chemical reactions of sulfur and lithium [55].

3.1.2. Fuel Cells

Fuel cells basically have similar operating principles and chemical reactions to battery cells in terms of converting chemical energy into electrical energy. The fuel cells are different from battery cells in that they need a constant supply of fuel and oxidizing agent for their operation, while battery cells contain closed stores of energy and are discarded or recharged, when discharged, by an external electricity supply. The fuel cells are not batteries, which store electrical energy, but generators which will produce electricity as long as they are supplied with fuel and oxidizing agent.

In general, fuel cells are classified according to electrolyte types. Even though fuel cell technologies share the same operating configuration, the electrolyte is a key factor which determines chemical reaction types, the range of operating temperature, and fuel cell performance. Fuel cell technologies are proton exchange membrane fuel cells (PEMFC), alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC), direct methanol fuel cells (DMFC), solid oxide fuel cells (SOFC), and molten carbonate fuel cells (MCFC). Among these technologies, automobile makers have found PEMFC to be the most suitable for application in electric vehicles. Because PEMFC chemical reactions occur between 60 and 100°C, a relatively lower temperature range than other fuel cell technologies, it has an advantage of fast start-up and frequent starts and stops. In addition, its power density is the highest among fuel cell technologies (0.35 – 0.6 W/cm^2), enabling automobile makers to dispel space and weight burdens for the fuel cell electric vehicle. Furthermore, PEMFC uses a solid electrolyte which is stable in the fuel cells (Ehsani et al., 2010).

Figure 14: Electrochemical Structure of PEMFC [78]



PEMFC fuel cells use a solid polymer electrolyte membrane which is coated with a catalyst, and it is typically fueled with hydrogen and air. Although methanol can be used as fuel for the PEMFC fuel cells, it is still being investigated. Hydrogen, or hydrogen containing a gas mixture, is fueled to the anode, and it is divided into electrons and hydrogen ions. The electrons flow to the external electrical circuit and the hydrogen ions transfer to the cathode. The returning electrons from the external electrical circuit and oxygen from external air make a chemical reaction at a catalyst of the cathode by producing water vapor [64].

While most automobile makers are supplied with batteries for their electric vehicles by battery manufacturers, they are participating in research and development from fuel cell system, stack and powertrain to complete fuel cell electric vehicles. In 2009, seven of the world leading automobile makers (Daimler, Ford, GM, Honda, Hyundai-Kia, Renault-Nissan, and Toyota) agreed a joint letter of understanding concerning development and production plans for fuel cell electric vehicles and build-up of a hydrogen infrastructure [79]. Daimler, GM, Honda, Hyundai-Kia and Toyota are developing the fuel cell electric vehicles based on PEMFC [80].

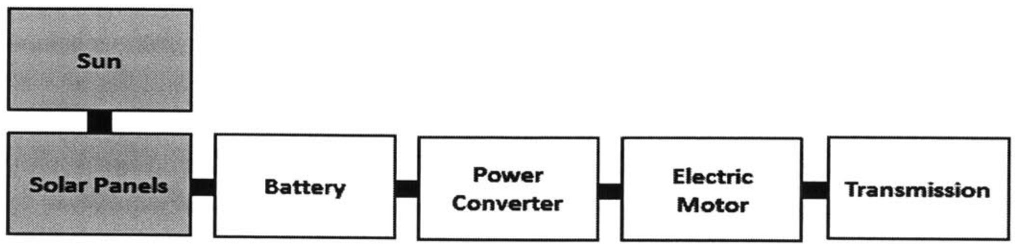
3.1.3. Other Technologies

Other technology research efforts concerning electric vehicles are ongoing, such as a capacitor, a flywheel, and solar cells. The capacitor is an electronic component, which electrostatically stores energy, and is commonly used in circuit boards of electronic devices. Capacitors for the electric vehicle are called ultracapacitors or supercapacitors because they are larger and store higher energy density than typical capacitors used for electronic devices. Although capacitors can be used for a primary energy storage system of a hybrid electric vehicle or a fuel cell electric vehicle, the current technology status of capacitors in power and energy density are not enough to be used for a primary energy storage system of a plug-in hybrid electric vehicle or a battery electric vehicle [81]. Since capacitors have a characteristic of fast charging and discharging, batteries in tandem with capacitors will improve battery life and power and energy density for electric vehicles. However, capacitors need to be enhanced to increase suitability for the electric vehicles and decrease costs [73].

A flywheel is a mechanical battery that stores rotational energy and provides energy to the powertrains of electric vehicles in the form of a mass spinning around an axis. Flywheels have advantages in supplying energy continuously when the energy source is not provided and in delivering the energy at rates beyond the energy source capability. However, they need further research and development for application to electric vehicles because of their complex stabilization mechanisms and high material costs [73].

Solar cells are another alternative energy source for the electric vehicle. Solar panels capture energy from the sun and convert the solar energy to electrical energy. The electrical energy is stored in the batteries of the electric vehicles and transferred to operate powertrains. In practice, solar cells are a complementary energy source in the electric vehicles. Solar panels are designed on the roof of the electric vehicles and help keep batteries charged. Currently, electric vehicles with solar panels are in the stage of being "concept cars" [82]. Solar panels on the roof of an electric vehicle do not generate enough energy to power the vehicle. Furthermore, the current technology status of the solar electric vehicles is prohibitive for commercialization. The solar electric vehicles need to develop a design that produces more power while reducing the costs [83].

Figure 15: Solar Electric Vehicle Structure [84]



3.2. Future Standard Format of Electric Vehicle Energy Sources

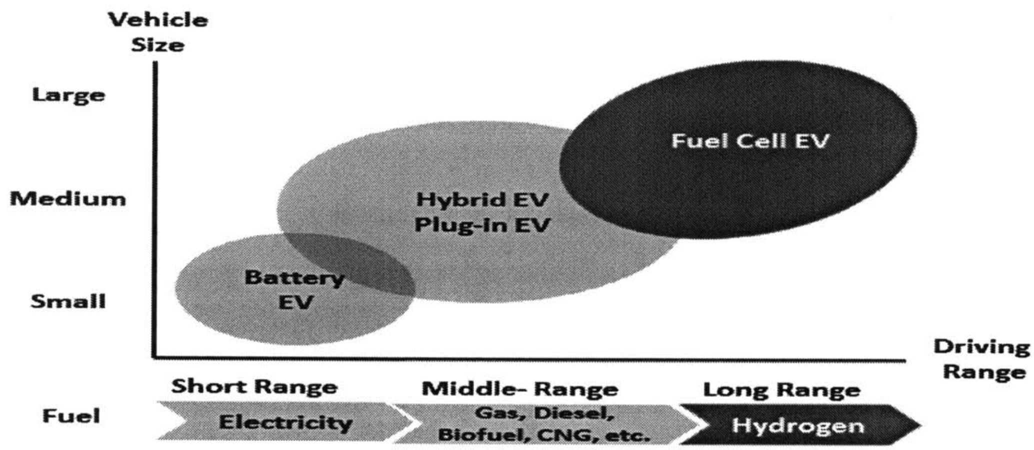
Although there are numerous ongoing research effort for the energy sources of the electric vehicles, the main trend of the electric vehicle energy source in the automotive industry can be narrowed down to lithium-ion batteries and fuel cells. Although automobile makers include both the battery electric vehicles and fuel cell electric vehicles in their technology roadmaps, there have been technology debates between these two.

The fuel cell electric vehicles are superior to the battery electric vehicles in having longer driving ranges, faster refueling time, and scalability to a wide range of vehicle sizes, even though the fuel cell electric vehicles need to solve critical issues of high costs, high price of fuel and lack of hydrogen fueling infrastructure. However, the commercialization prospects of the battery electric vehicle and the fuel cell electric vehicle cannot be predicted simply by technology enhancement and cost reduction potentials. For the success of commercialization, one technology must surpass the other in performance, cost, infrastructure, customer evaluations, policies and industry ecosystems.

The outcome of the technology competition between the battery electric vehicles and the fuel cell electric vehicles depends on how customers value them over conventional internal combustion engine vehicles and which technologies are more favored in subsidies, infrastructure and R&D investments. In addition, the competition's result will be affected by how the automobile makers market the battery electric vehicles and the fuel cell electric vehicles. While the batteries for the electric vehicles are supplied by battery manufacturers, the automobile makers are developing and manufacturing the fuel cell systems and stacks for the fuel cell electric vehicles. Self-manufacturing of the fuel cell can give the automobile makers priority in marketing the fuel cell electric vehicles.

The automobile makers and experts predict that the battery electric vehicles and the fuel cell electric vehicles will coexist, depending on driving ranges and vehicle sizes in technology roadmaps. Toyota has a big picture of its future vehicle portfolio (Figure 15); The battery electric vehicle will be popularized for commuting or delivery purposes with a small sized vehicle within a short driving distance [85]. The fuel cell electric vehicle will be optimized for passenger vehicles or trucks with a medium- or large-sized vehicle within middle or long driving distances. By being usable for a wide range of purposes, the hybrid electric vehicle and plug-in hybrid electric vehicle will fill the gap between the battery electric vehicle and the fuel cell electric vehicle.

Figure 16: Future Mobility Portfolio of Toyota (Toyota Motor Corporation, 2013)



However, this competition will be determined by which technology will be competing with the other. Whether the battery will be defeated by the fuel cells, or dominant, or coexist with the fuel cell for the electric vehicles, will be dependent on how the battery technology evolves and how the main players in battery technology will fare in the market. While automobile makers are already vertically integrating developing and manufacturing of the fuel cells and the fuel cell electric vehicles, they are being involved in manufacturing the battery electric vehicles, relying on the battery supply from battery manufacturers. Thus, the electric vehicle battery industry is the main player in this technology competition, which will be responsible for the future of the battery electric vehicle.

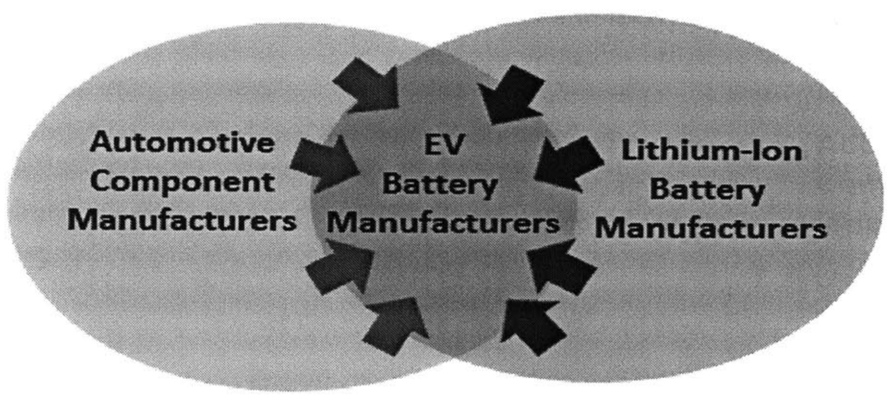
Chapter 4: Global Analysis of the Electric Vehicle Battery Industry

Although Prius and Lexus still use nickel-metal hydride batteries for their hybrid electric vehicles, most electric vehicles use lithium-ion batteries for their main energy sources. Thus, this analysis of the electric vehicle battery industry focuses on the lithium-ion battery industry itself and on manufacturers of the electric vehicle batteries. More specifically, I will analyze the current business environment of lithium-ion battery industry and the corporate strategies of its manufacturers. In the next chapter, I will offer suggestions for strategies of the electric vehicle battery industry on the basis of this analysis.

However, in terms of business origins, lithium-ion battery manufacturers for the electric vehicles in the market largely can be divided into: 1) lithium-ion battery manufacturers for consumer electronic products and 2) automotive component or device manufacturers. The lithium-ion battery manufacturers for the consumer electronic products have diversified their applications into electric vehicles. In contrast, the automotive product manufacturers started their lithium-ion battery businesses for electric vehicles based on their conventional automotive battery manufacturing capabilities or business and technology know-how of the automotive product industry: lead-acid batteries for SLI batteries (starting, lighting, and ignition), automotive power systems, electronics, seats, etc.

Therefore, this analysis will also include other applications of the lithium-ion batteries that some electric vehicle battery manufacturers have in their business portfolios. In addition, this analysis will include conventional battery businesses that the other electric vehicle battery manufacturers have in their business portfolios.

Figure 17: Classification of Electric Vehicle Battery Manufacturers in Business Origins



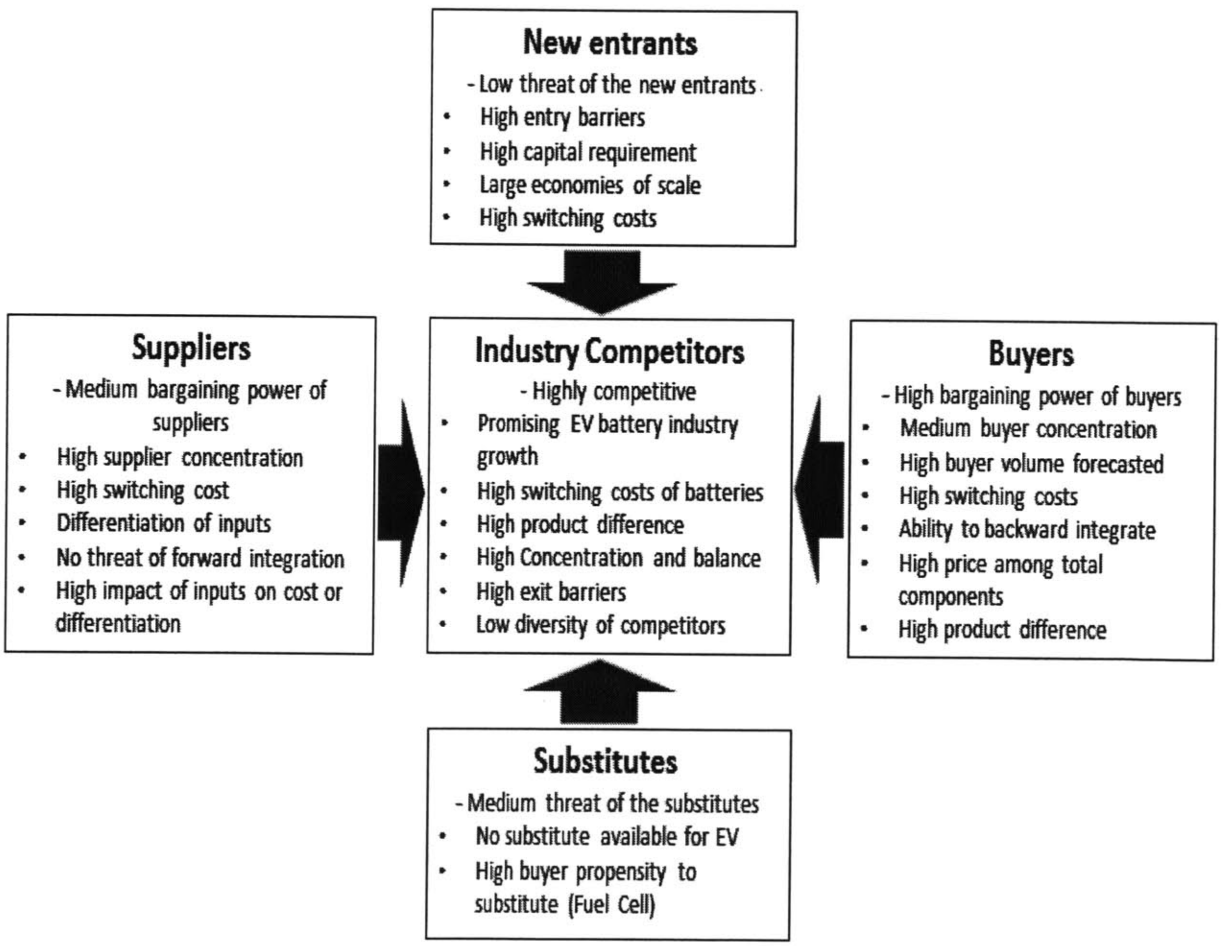
4.1. Electric Vehicle Battery Industry

As the electric vehicles become promising businesses, the battery industry for the electric vehicles has been competitively growing up. Although the commercialization of the electric vehicles began in earnest in the late 2000s, the battery industry for the electric vehicles has tried to expand their client bases and increase sales, and has competed to achieve market leadership in several ways. Furthermore, as mobile electronic products such as smartphones and tablet PCs have been forecast to slow down their growth in 2014, the lithium-ion battery manufacturers are desperately expanding their businesses for the electric vehicle battery. In the next section, using through Michael Porter's Five Forces Model, the competitiveness and attractiveness of the electric vehicle battery industry are analyzed [86].

4.1.1. Industry Competitors: Intensity of Rivalry

As the electric vehicle battery industry is forecast to grow up fast, its competition is being accelerated. Since the batteries of the electric vehicles are customized to the electric vehicles and the battery switching costs are high, the battery manufacturers have competed to achieve dominance in the market.

Figure 18: Five Forces Model Analysis of the Electric Vehicle Industry



The electric vehicle battery industry is expecting substantial industry growth. Depletion of fossil fuels and the environmental threat of CO_2 emissions are awakening governments and consumers and increasing public awareness of electric vehicles. Electric vehicle demand is being stimulated by favorable government policies: CO_2 emission regulations, legal targets, and financial support for electric vehicle purchases and for the R&D of the electric vehicle industry and of academics. As the electric vehicle industry is forecast to sharply grow, the electric vehicle battery industry is expected to enjoy similarly its promising growth. However, the energy sources of the electric vehicle can be various, from lithium-ion battery, to other battery technologies, to fuel cells. Even though the lithium-ion batteries dominate the market for the main energy sources for the electric vehicle, the battery industry growth for the electric vehicle may change according to the future standardized technology of the electric vehicle energy sources.

Secondly, the switching costs of the batteries for the electric vehicles are high. Compared to the consumer electronic products, the contracts between battery manufacturers and automobile makers are relatively long-term and exclusive. Although automobile makers have contracts with more than one battery manufacturer, each vehicle model is supplied batteries by a sole battery manufacturer. Because batteries for the electric vehicles are the main energy sources which threaten to internal combustion engine vehicles, and battery manufacturers are actively taking part in the stage of designing electric vehicles in order to secure the space for the batteries in the vehicles. Meanwhile, the electric vehicle battery industry has high product difference because the electric vehicle batteries are highly customized to the designs of the electric vehicles.

Next, the electric vehicle battery industry has high concentration and balance. The electric vehicle battery market is concentrated on major manufacturers in the electric vehicle battery industry. Even though the late movers in the electric vehicle battery industry are striving to achieve new clients as well as secure current clients, it is very hard to expand their client pool because of the high switching costs.

Lastly, the electric vehicle battery industry has low diversity of competitors with respect to energy sources for electric vehicles. Even though automobile makers are targeting to launch the fuel cell electric vehicles within 5 years, they need to improve performance, price, and safety of the fuel cell electric vehicles for the commercialization. Also, the electric vehicle battery industry has high exit barriers. It needs large capital investments in R&D, operations and scale-ups.

4.1.2. New Entrants: Threat of New Entrants

The electric vehicle battery industry has high entry barriers with respect to high capital requirement, large economies of scale, and high switching costs. Even though new ventures such as Ener1 and A123 systems entered the electric vehicle battery industry based on high competency of technologies and grants of the U.S. government, they were not able to survive because the electric vehicle market grew so slowly. Both companies filed for bankruptcy in 2012 [87], [88]. Without competencies in high capital investment and large economies of scale, new entrants cannot survive in this industry.

The electric vehicle battery industry requires high capital investment. It continues to invest to develop battery and manufacturing technologies, identify new materials and ramp up capacity. Since batteries are commodity products, large firms can produce them at lower cost per unit. The customized design, performance and safety issues of the electric vehicle batteries result in high switching costs. Thus, the large firms are preoccupied with market leadership in this industry, and the probability of threat of the new entrants is very low.

4.1.3. Substitutes: Availability of Substitutes

With respect to entire vehicles, the internal combustion engine can be a substitute for the electric vehicle batteries. The relatively high price and low infrastructure of the electric vehicles hinders the market competition with the internal combustion engine vehicles. The technology familiarity of the conventional passenger cars to the final customers is an obstacle to purchasing an electric vehicle because they distrust the latter's performance and safety.

Regarding alternative energy sources for the electric vehicle, no substitute for the electric vehicle batteries is available in the market. Studies and researches in next generation of electric vehicle energy sources are vigorously being conducted. Automobile makers are introducing concept cars of the fuel cell electric vehicles, and trying to bring forward launches of the fuel cell electric vehicle. However, lithium-ion batteries are currently optimal for the commercial applications in the electric vehicles.

On the other hand, automobile makers' inclination to shift to the fuel cell is very high. Automobile makers are directly investing the fuel cell technologies and the commercialization of the fuel cell electric vehicles. If automobile makers succeed in this commercialization, they can have the backward vertical integration of the fuel cell electric vehicles, and they will achieve advantages in the value chain. In addition, the superiority of the fuel cell in power and energy density and long electric driving range results in high attractiveness to automobile makers.

4.1.4. Buyers: Bargaining Power of Buyers

Worldwide automobile makers have been actively involved in the electric vehicle businesses and they have strong bargaining power in purchasing the batteries for the electric vehicles because many lithium-ion battery manufacturers for the electric vehicles are available in the market. However, automobile makers choose strategic partners among electric vehicle battery manufacturers, because their purchasing volumes are not enough to diversify the suppliers of the electric vehicle batteries. Besides, the battery manufacturers are involved in the early stage of the electric vehicle development, and the switching costs are high because the batteries are customized to the electric vehicles.

In addition, automobile makers have abilities to achieve backward vertical integration. Automobile makers such as Toyota and Honda have participated in battery pack system integration businesses for the electric vehicles through joint ventures with battery manufacturers. Primearth is a joint venture of Toyota and Panasonic and Blue Energy is a joint venture of Honda and GS Yuasa. Furthermore, Tesla Motors announced that it would build a lithium-ion battery factory which is able to supply batteries to 500,000 electric vehicles per year [89]. Panasonic has announced plans to invest in the lithium-ion battery factory of Tesla. The main reason why automobile makers are interested in backward vertical integration is that the electric vehicle batteries have a large impact on the performance and quality of the electric vehicles. The electric driving ranges and safety issues are dependent on the battery capabilities. Also, the battery of the electric vehicle results in additional costs over a conventional internal combustion engine vehicle, although the price increase depends on the kind of electric vehicle, the battery capabilities, and the development stages of the electric vehicles [90].

4.1.5. Suppliers: Bargaining Power of Suppliers

Suppliers of raw materials for the electric vehicle batteries have medium bargaining power. The cathode cost makes up 40% of lithium-ion cell material costs [91], and the cathode is the most important material to impact the performance and the price of the electric vehicle batteries. Even though the major leading suppliers are different, depending on cathode materials such as LMO, NCA and NMC, the cathode material market for the lithium-ion battery is an oligopoly. Furthermore, other raw materials including anodes, separators and electrolytes for the lithium-ion batteries are respectively dominated by the major leading suppliers. However, the lithium-ion battery industry has tried to diversify the suppliers by looking for competitive prices of raw materials, and identifying cost-competitive raw materials.

4.2. Business Scope and Strategy of Electric Vehicle Battery Manufacturers

The main battery technology for the electric vehicle commercialization is lithium-ion batteries and the electric vehicle battery industry focuses on manufacturing and R&D of lithium-ion batteries. Even though lithium-ion battery demand for electric vehicles is expected to grow extensively, the sales ratio of lithium-ion batteries for the electric vehicle was only 15% in 2012. (Table 9) Thus, the lithium-ion battery manufacturers are highly reliant on the consumer electronics.

On the other hand, the electric vehicle battery industry can be originally divided into the lithium-ion battery manufacturers and the conventional automotive battery manufacturers. As the lithium-ion batteries have become the main energy resources for the electric vehicles, the lithium-ion battery manufacturers for the consumer electronics have expanded their business portfolios to the electric vehicle batteries, and the conventional automotive battery manufacturers have diversified with the lithium-ion batteries. Since the business environments for automobile makers are different from those for OEMs of consumer electronics, the competition structure among the lithium-ion battery market for the electric vehicle is distinct from the overall lithium-ion battery market competitions.

Table 9: Global Lithium-Ion Battery Market Status and Forecast (Unit: m USD) [92]

	2011	2012	2013E	2014F	2015F	2016F	2017F	2018F	CAGR
Electric Vehicle	1,127	2,111	2,944	3,955	5,448	8,130	11,497	16,965	72.0%
Consumer Electronics	10,479	11,562	11,609	13,127	14,170	14,862	14,973	14,963	7.4%
ESS	184	214	609	728	1,130	1,533	1,950	2,655	70.6%
Total	11,790	13,887	15,162	17,810	20,748	24,525	28,420	34,583	24.0%

※ E: Expected, F: Forecast

※ ESS: Energy Storage System

4.2.1. Market Leaders

Market leaders are leading the electric vehicle battery industry in R&D, strategies and executions. LG Chem is one of the top 3 market-leading companies in the overall lithium-ion battery industry. Based on businesses of petrochemicals and IT and electronic materials, it has diversified energy solutions including batteries for consumer electronics and electric vehicles and energy storage systems. Because LG Chem was originally founded as a chemical company, it has the advantages of backward vertical integration for the electric vehicle battery business. Since LG Chem entered the electric vehicle battery market, it has aggressively expanded its networks with automobile makers and geographic locations (the U.S., EU, China and Korea). LG Chem has secured over 10 international automobile maker customers including GM, Hyundai-Kia, Renault, Ford and Volvo. It has heavily invested R&D in as well as scaling-up based on quick decision making and “speed management” [93].

Panasonic is another top 3 market leading company in the overall lithium-ion battery industry. It is a large conglomerate company which has diverse businesses from consumer electronics to home appliances and batteries to beauty and healthcare [94]. It has the advantages of forward vertical integration for the lithium-ion battery business because it has internal demand for lithium-ion batteries. Panasonic has built a well-organized battery portfolio from primary batteries to rechargeable batteries. Its battery business portfolio includes zinc carbon, alkaline, lead-acid, nickel-cadmium, nickel metal hydride and lithium-ion batteries. Moreover, it has expanded the lithium-ion battery business with strategic decision making and partnerships. The M&A of Sanyo in 2009 gave Panasonic the opportunity to become one of the top 3 leading companies in the lithium-ion industry [95]. The strategic partnership with Tesla enables

Panasonic to be a market leader in the electric vehicle battery industry. Panasonic is planning to invest in Tesla's "Gigafactory" for the lithium-ion batteries [96].

Johnson Controls is a global diversified company in the building and automotive industries. Johnson Controls has expanded its business portfolios through several M&As and entered the automotive battery business with the acquisition of Globe-Union in 1985. It has strong business networks and know-how in the automotive industry, and it is known for automotive products including lead-acid automotive batteries, SLI batteries (starting, lighting, and ignition), and interior systems for automobiles. It has invested in the R&D of the battery technologies through partnerships with an advanced lithium-ion battery developer, PolyPlus Battery Co., and academic research centers [97].

AESC is a joint venture of Nissan Motor and NEC, founded in 2007. AESC is a specialized company for the lithium-ion batteries for the electric vehicle based on the automotive technologies of Nissan Motor and the lithium-ion battery technologies of NEC. It is highly dependent on the demand for lithium-ion batteries for Nissan's electric vehicles [98].

4.2.2. Market Contenders

Market contenders aggressively try to achieve the market leadership with advanced technologies by beating market leaders. Samsung SDI is the other top 3 market leading company in the overall lithium-ion battery industry with LG Chem and Panasonic. Even though its sales revenue was ranked at the top in the small and medium-sized lithium-ion battery market in 2013, and it has the technology leadership of the lithium-ion batteries (Table 10), Samsung SDI has struggled to expand clients of the electric vehicles. Since Samsung SDI was originally founded as a display manufacturer in 1970 [99], it had focused on businesses with consumer electronics until it established a joint venture with Bosch for the electric vehicle battery business in 2008. In 2012, the joint venture with Bosch was ended [100], and in 2014, Samsung SDI announced its intention to merge in July with the chemical division of Cheil Industries, which holds core material technologies and manufacturing competencies for secondary batteries [101]. Through the M&A with Cheil Industries, Samsung SDI would achieve the advantages of backward vertical integration. In addition, Samsung SDI is planning to construct two lithium-ion battery plants in Xi'an, the capital city of northwest Shaanxi province in China. It agreed to cooperate with two Chinese companies, the ARN Group and Xi'an High-Technology Group in a memorandum of understanding with the government of Shaanxi province [102]. It is trying to achieve the market leadership in the electric vehicle batteries through vertical integration and geographic expansion.

Hitachi Vehicle Energy is a joint venture of Hitachi, Shin-Kobe Electric Machinery and Hitachi Maxwell for the lithium-ion batteries of the electric vehicles. Since Hitachi has accumulated business know-how and technology competencies in the automotive industry through Hitachi Automotive Systems and in the lithium-ion batteries through Hitachi Maxwell, Hitachi Vehicle Energy has advantages in the electric vehicle battery business. Hitachi Vehicle Energy is building up its business portfolio of inverters, motors and the lithium-ion batteries for hybrid electric vehicles [103].

Toshiba is one of the global leading consumer electronics companies. It has a business portfolio from business and industrial products to consumer electronic products. Since Toshiba has internal demand for the lithium-ion batteries, it has the advantages of forward vertical integration. In addition, its business networks and R&D experience should help its lithium-ion battery business for the electric vehicles. Furthermore, it has invested in new battery technologies so that it holds patents on SCiB™ batteries (super charge ion battery) which are based on the lithium-titanate batteries (LTO). Toshiba's SCiB™ batteries are superior in performance, length of life, safety and charging time [104].

Table 10: Shipping Quantity of Small and Medium-Sized Lithium-Ion Batteries in 2013 (Unit: m Battery Cell) [92]

Company	Origin	Shipping Quantity	Market Share
Samsung SDI	Korea	1,096.1	21.7%
LG Chem	Korea	718.1	14.2%
Panasonic	Japan	604.3	12.0%
Sony	Japan	387.0	7.7%
Risun	China	280.3	5.5%
ATL	China	275.5	5.5%
BYD	China	251.3	5.0%
Coslight	China	170.1	3.4%
Hitachi Maxwell	Japan	134.5	2.7%
BAK	China	98.6	2.0%
Others		1,038.8	20.6%
Total		5,046.6	100.0%

※ Small: commonly used in consumer electronics, Medium: commonly used for the electric vehicles, power tools and E-bikes

SK Innovation started as an oil refining company in 1962, and it expanded its business into the lithium-ion batteries for the electric vehicles and industrial and electronic materials. SK Innovation is enhancing the value chain of its lithium-ion battery business by in-house manufacturing from separators and electrodes to battery cells and packs. SK Innovation has its proprietary battery management technologies such as cell balancing software and state-of-charge prediction algorithm [105]. In addition, it has a joint venture with Continental AG, which is named SK Continental E-motion, for the electric vehicle battery business [106].

4.2.3. Market Challengers

Market challengers try to challenge the market for the technology competitions and market shares, but they are not strong competitors in strategies, technologies and executions.

BYD became world-famous when Warren Buffett purchased a $232 m stake in BYD [107]. It has a diversified business portfolio from consumer electronics and new green energy to automobiles. BYD entered the automobile industry by purchasing Xi'an Tsinchuan Auto in 2003, and it is manufacturing electric vehicles as well as conventional internal combustion engine vehicles. BYD has the internal demand for lithium-ion batteries for electric vehicles and consumer products [108], and has a strategic partnership with Daimler AG for the business in China [109]. However, BYD is struggling to expand its global clientele for electric vehicle batteries.

GS Yuasa is a 100-year-old specialized battery company in Japan. Its manufacturing ranges from conventional automotive, motorcycle, and industrial batteries to power supply systems and membrane systems. It has technology and manufacturing competencies in the lithium-ion as well as nickel-metal hydride batteries [110]. However, GS Yuasa does not have experience in volume manufacturing of the lithium-ion batteries, and it is hard for GS Yuasa to scale up without strong financial support [111]. Thus, GS Yuasa has established strategic partnerships for manufacturing and developing electric vehicle batteries. GS Yuasa has a joint venture with Honda, which is named Blue Energy, for electric vehicle batteries, and it has established a joint venture with Bosch and Mitsubishi, which is known as Lithium Energy and Power GmbH & Co. KG, for R&D of the next generation lithium-ion battery technologies [112].

A123 Systems is an advanced lithium-ion battery developer and manufacturer based on nanophosphate materials licensed from Massachusetts Institute of Technology. Even though A123 Systems possesses R&D competencies of advanced lithium-ion technologies and received a $249 m grant from the U.S. Department of Energy for constructing the manufacturing facilities, it went bankrupt in 2012 because of lack of experience in volume manufacturing and safety issues [113]. Wanxiang Group, which is a Chinese automotive group, purchased A123 Systems in 2013 [114] and acquired Fisker Automotive through its bankruptcy auction in 2014 [115]. The bankruptcy of A123 Systems suggests how important volume manufacturing competencies and safety issues are in the electric vehicle battery industry. Furthermore, it shows the difficulties for new entrants in competing with giant market leaders in the electric vehicle battery industry.

4.2.4. Market Followers

Market followers are doing their business in the limited business areas of an industry. Market followers do not strategically advance the market and technologies, and follow the industry. Primearth is a joint venture of Toyota and Panasonic [116], and Blue Energy is a joint venture of Honda and GS Yuasa [117]. Primearth and Blue Energy integrate pack systems as they purchase battery cells from their partners (Panasonic and GS Yuasa). They were originally founded for the enhancement of the battery supply chains for the electric vehicles.

Table 11: Global Analysis of the Electric Vehicle Battery Manufacturers

		Strength (+) and Weakness (-)
Market Leaders	LG Chem	+ A Li-ion battery provider for consumer electronics + Backward vertical integration: chemical and electronic materials + Strong relationship with automobile makers + Geographic diversification for EV battery: US, EU, China, Korea
	Panasonic	+ A Li-ion battery provider for consumer electronics + Diversified business portfolio + Forward vertical integration: consumer electronics + Strong relationship with automobile makers - Limitation in geographic diversification for EV battery
	JCI	+ A conventional automotive battery provider + Strong relationship with automobile makers - Limitation in applications of Li-ion batteries: focus on EV - Limitation in geographic diversification for EV battery
	AESC	+ A joint venture with Nissan and NEC group - High dependence on Nissan and limitation to expand clients - Limitation in applications of Li-ion batteries: focus on EV - Limitation in geographic diversification for EV battery
Market Contenders	Samsung SDI	+ A market leader in the overall Li-ion battery industry + A Li-ion battery provider for consumer electronics + Backward vertical integration: chemical and electronic materials + Diversified business portfolio in energy solutions - Low experience and weak relationship with automotive industry - Limitation in geographic diversification for EV battery
	Hitachi Vehicle Energy	+ Forward vertical integration: consumer electronics + Business and R&D know-how in consumer electronics and automotive industry (Hitachi Maxwell and Hitachi Automotive Systems) - Limitation in applications of Lithium-Ion batteries: focus on EV - Limitation in geographic diversification for EV battery
	Toshiba	+ Forward vertical integration: consumer electronics + Biz and R&D know-how in consumer electronics and automotive industry - Limitation in geographic diversification for EV battery
	SK Innovation	+ Backward vertical integration: chemical and electronic materials + A joint venture with Continental AG - Limitation in geographic diversification for EV battery
Market Challengers	BYD	+ Forward vertical integration: automotive business - High dependence on Nissan and limitation to expand clients - Limitation in applications of Li-ion batteries: focus on EV - Limitation in geographic diversification for EV battery
	GS Yuasa	+ A conventional automotive battery provider - Lack of experience in volume manufacturing - Limitation in financing for the scale-up
	A123 Systems (B456)	+ A developer and manufacturer of advanced Li-ion batteries - Financial problems - Limitation in applications of Li-ion batteries: focus on EV - Limitation in geographic diversification for EV battery
Market Followers	Primearth Blue Energy	+ A joint venture of automobile makers and battery manufacturers - Pack system integrators

4.3. Implications for Developing Strategies of the Electric Vehicle Battery Industry

The analysis of business scopes and strategies of the electric vehicle battery manufacturers shows its key considerations for developing the strategies: R&D investment, economies of scale, strategic partnerships and vertical or horizontal integrations. The electric vehicle battery manufacturers are investing in R&D to achieve technology initiatives of the next generation of electric vehicle batteries. In addition, the electric vehicle battery manufacturers are investing in expanding production capacities to achieve economies of scale and market leadership. Also, the electric vehicle battery manufacturers have set up strategic partnerships and established joint ventures in order to complement their weaknesses in technologies, business networks and experience. Lastly, the electric vehicle battery manufacturers have done backward or forward vertical integrations to achieve technology or cost leadership in the market.

Chapter 5: Recommendations for the Electric Vehicle Battery Industry

5.1. Technology Advancements

The main reasons that the electric vehicle market has been growing slowly are short electric driving range, lack of charging infrastructure, long charging time, and expensive vehicle price. These reasons are directly related to battery capabilities. Furthermore, the electric vehicle battery industry needs to outcompete the fuel cell in technology and cost. Thus, the electric vehicle battery industry should invest in enhancing the current lithium-ion battery technologies for cost leadership and developing the next generation battery technologies for technology leadership. The R&D investments should include identification of the raw materials for cathodes, anodes and electrolytes, and manufacturing innovations in order to improve yield and defect rates, and reduce costs. In addition, the R&D investments for the next generation battery technologies should not stick to the lithium-ion battery technologies. Even though the lithium-ion battery technologies are currently optimal for the electric vehicles, they are not the best technologies for the future. The electric vehicle battery industry should identify and commercialize the next generation technologies of energy sources.

5.2. Strategic Partnerships

Strategic partnerships are being vigorously enacted among automotive makers, battery manufacturers and developers, and automotive component manufacturers. The importance of technology standards, charging infrastructure, high switching costs, and economies of scale force the electric vehicle battery industry to set up strategic partnerships or joint ventures. Even though strategic partnerships give it opportunities to expand its business scope and develop technology capabilities, short-term partnerships would not be beneficial since they risk getting core technologies or business skills stolen. Therefore, it should choose strategic partners with long-term perspective.

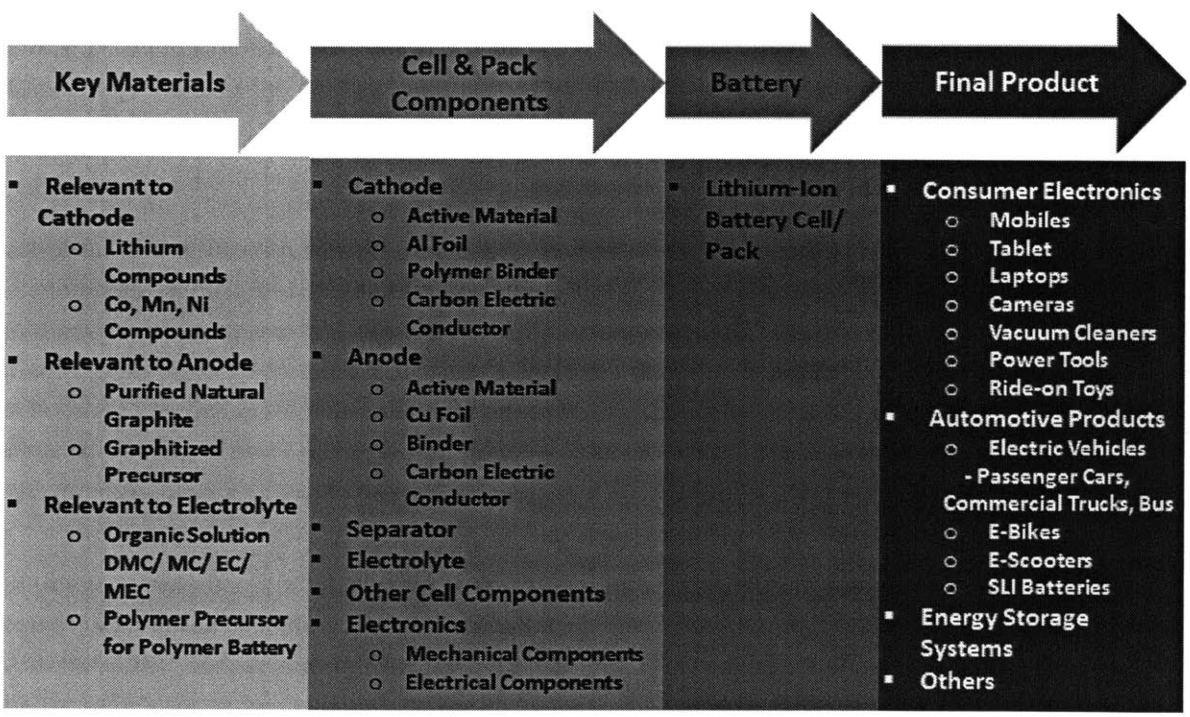
Besides, the electric vehicle battery industry should strengthen its strategic partnerships with emerging electric vehicle companies. The conventional automotive industry is devoting itself to commercializing fuel cell electric vehicles, and the electric vehicle battery will have to compete directly with the fuel cell in the near future. If the electric vehicle battery industry firmly develops strategic partnerships with the emerging electric vehicle companies, it can grow together with them. The strategic partnership of Panasonic and Tesla is the prime case. As Panasonic has nurtured the strategic partnership with Tesla since 2011 [118], Tesla has strengthened its relationship with Panasonic by extending its battery cell supply contract through 2017. Panasonic also is considering investing in Tesla's "Gigafactory" for lithium-ion batteries [119].

5.3. Enhancement of Value Chain

The electric vehicle battery industry should enhance its value chain. Since the raw material prices and supplies affect the component prices and supplies of the lithium-ion battery components, the electric vehicle battery industry should extend its management of the value chain from the first-tier vendors to lower-tier vendors. Furthermore, it should try to diversify the component suppliers or consider in-house manufacturing of key components, such as cathodes or anodes, in order to enhance quality and reduce cost.

Horizontal integration can be another solution because the electric vehicle battery industry is looking for the next generation of technology. While it is developing other battery technologies or complementary products for the batteries such as flywheels or ultracapacitors, the electric vehicle battery industry could seek synergies in developing battery technologies.

Figure 19: Value Chain of the Lithium-Ion Battery Industry [75]



5.4. Diversification of Applications

As the demand for electric vehicles has slowly increased, the demand for lithium-ion batteries for electric vehicles has been estimated to consist of 19% of the total lithium-ion battery demand in 2013 (Table 9). The demand for lithium-ion batteries for electric vehicles alone is enough to achieve the economies of scale in manufacturing. Thus, the electric vehicle battery industry should consider diversifying the applications of the batteries. Lithium-ion batteries are currently used for consumer electronics such as smartphones, tablet PCs, laptops and cameras.

The electric vehicle battery industry should expand the applications from consumer electronics and electric vehicles to other automotive vehicles and products. It should develop batteries not only for passenger vehicles but also for commercial trucks or buses. In addition, the SLI batteries, which are commonly lead-acid batteries, can be another potential application of the lithium-ion batteries. Furthermore, energy storage system can be another alternative use for lithium-ion batteries as the demand for renewable green energy is growing and energy storage systems are needed to store the energy which is generated by renewable green sources.

5.5. Value Competition

The electric vehicle battery industry should not focus on price competition but concentrate on value competition. The current overheating competition in R&D and scale-ups of manufacturing would cause price wars with overcapacity in the electric vehicle battery industry. Such price wars, which the semiconductor industry and LCD (Liquid Crystal Display) industry experienced, resulted in leaving only the major players, who could endure the undervalued market price in order to survive in the market, and wiping out the other players. In the case of the LCD industry, the survivors of the price wars are struggling to compete with the advanced display technologies such as LED (Light-Emitting Diode) and OLED (Organic Light-Emitting Diode) after their short period of glory. Thus, the electric vehicle battery industry should consider how it delivers and improves the valueprovided rather than price competition. It should take into account how to enhance customer business value by restructuring business strategies.

5.6. Strengthening the Industry's Power through Strategic Alliances

The electric vehicle battery industry should strengthen its industry's power through strategic alliances in order to nurture itself and promote itself to final customers. The electric vehicle industry is influenced by external factors such as government environmental policies, regulations, and NGOs. Government financial support and investment are very critical to increase electric vehicle sales and to develop technologies. Expanding charging infrastructure is one of the important factors to popularize electric vehicles, but the electric vehicle industry cannot provide complete charging infrastructure itself. Also, the electric vehicle battery manufacturers have a limited ability to promote the superiority of the electric vehicles because they are not selling their products to the final customers. If the fuel cell electric vehicles are commercialized, the automotive industry will focus on promoting the fuel cell electric vehicles. Thus, through the strategic alliances, the electric vehicle battery industry should intensify its negotiations with government to improve infrastructures and increase public awareness of battery electric vehicles.

Conclusion

Tesla's plan of constructing the "Gigafactory" of the lithium-ion batteries for the electric vehicles and several public announcements of M&A and joint ventures show accelerating competition in the electric vehicle battery industry. In addition to the internal competitions within the electric vehicle battery industry, it needs to compete for technologies of the standard energy source with other alternative technologies such as fuel cells for the electric vehicles. The overheating competition of the internal and external electric vehicle battery industry can be expected to cause price wars and restructuring of the market by leaving only a few major players who can survive. Therefore, the electric vehicle battery industry should achieve technology, cost and market leadership in order to survive as standard energy source providers of the electric vehicles in the fierce competition. It should invest in technology advances for the next generation of battery technologies, raw materials, and manufacturing. Furthermore, the electric vehicle battery industry should enhance the value chain in order to secure stable supplies and competitive cost structures as well as high performance. Next, the diversification of the applications is important to obtain economies of scale because the demand for lithium-ion batteries for the electric vehicle is growing but not enough to achieve cost advantages in volume manufacturing. Also, the electric vehicle battery industry should avoid price competition and focus on value competition. Lastly, the electric vehicle battery industry should strengthen its industry's power through strategic alliances.

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