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ASSESSMENT OF NEXT-GENERATION ELECTRIC VEHICLE TECHNOLOGIES

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EXECUTIVE SUMMARY

Automakers and governments are actively investigating what it will take to shift to a fleet of electric vehicles in various markets around the world. Among the critical questions about such a transition are the pace of battery technology development and how quickly its costs are reduced. Manufacturers are continually making technology improvements, including increasing range and reducing costs, to increase the viability of electric vehicles. A key question is how quickly next-generation electric vehicle production might allow greater economies of scale and greatly increased electric vehicle range at reduced electric vehicle prices.

This study analyzes emerging light-duty electric vehicle technologies in terms of their performance characteristics and costs. We assess the key technology trends in electric vehicle attributes, such as electric range and battery cost, which are widely expected to impact the broader consumer attractiveness of electric vehicles. The scope of the work includes an analysis of the specifications of major electric vehicle models in China, Europe, Japan, and the United States through 2015. An analysis of evolving battery costs beyond 2020 is presented. This analysis is based on a synthesis of public data from energy laboratories, academic research literature, and supplier and automobile company announcements.

Figure ES-1 shows the estimated decline in battery pack manufacturing costs and the associated increasing sales of electric vehicles. As shown in the figure, global 2015 sales exceeded 500,000 vehicles, while the average battery costs were approximately $300 per rated kilowatt-hour (kWh) for industry leading, high volume manufacturers. Technological advancements in leading lithium-ion chemistries in conjunction with greater economies of scale are expected to decrease battery pack costs through 2023. The projected decrease to below $200 per kilowatt-hour in 2020 and beyond for leading companies is based on best-available bottom-up engineering analyses on lithium-ion battery manufacturing at increased production volumes. Battery cell-level costs are typically 20-40% lower than the battery pack-level costs shown.

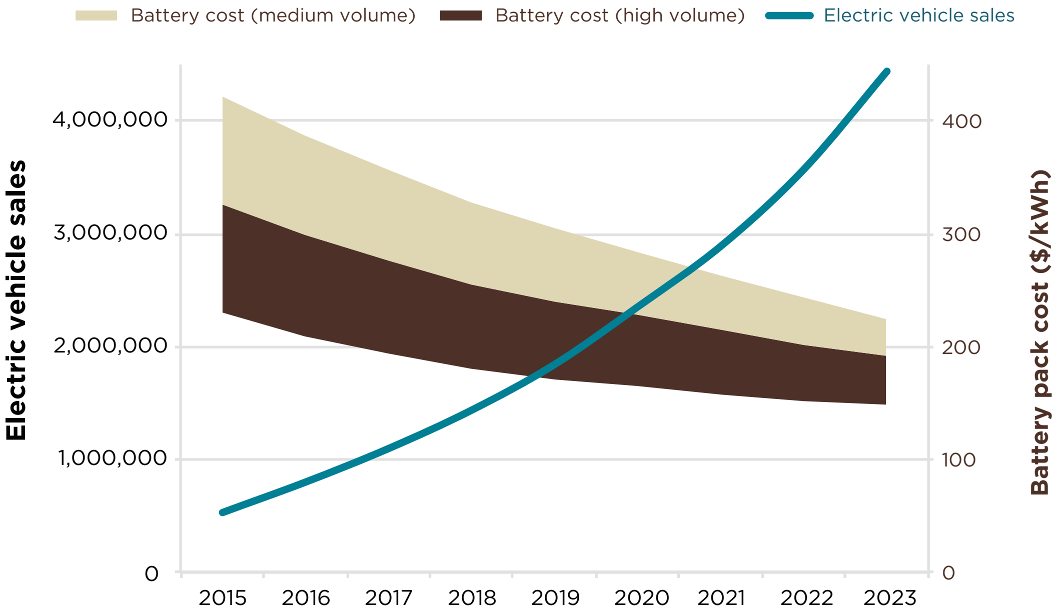

Figure ES-1. Scenario for estimated electric vehicle sales and battery pack cost

The projected electric vehicle growth in Figure ES-1, to sales of more than 4 million electric vehicles in 2023, amounts to an approximate 30% compounded annual industrywide sales growth rate. Within this scenario, high volume companies like Tesla and BYD are assumed to produce over 300,000 electric vehicle sales annually, whereas medium volume companies are assumed to produce approximately 100,000 electric vehicle sales per year in the 2020-2023 time frame. The associated battery pack costs are based on indexing the projected automobile companies' electric vehicle deployment growth to best available public literature on battery pack production costs. Overall, this assessment is based on battery manufacturing of known lithium-ion battery chemistries being considered and with electric vehicle sales amounting to approximately 5% of global vehicle sales in 2023.

Based on our analysis, we draw the following three conclusions:

> ***Increased diversity of electric vehicle models is creating more alternatives across all market segments.*** Manufacturers are increasingly offering all-electric or plug-in hybrid models in most vehicle classes. Over 25 different plug-in electric models were offered in 2015 in the three largest national markets of China, Europe, and the U.S. An assortment of plug-in options for smaller cars, sedans, crossover sport-utility vehicles, low cost brands, luxury brands, and models with all-wheel drive, are more broadly meeting consumer demands.
>
> ***Electric vehicles with increased electric range are entering the market from 2016-2018.*** Battery technology advancements and greater production volume are allowing companies to offer electric vehicles with improved performance and range. More vehicles with greater battery capacity, electric efficiency, and range have been sold in steadily larger numbers through 2015. Announced next-generation Chevrolet, Nissan, and Tesla models indicate mass-market cars with at least 200 miles of electric range will accelerate this trend.
>
> ***Companies are making the move to higher production and lower cost.*** Vehicle and battery manufacturers, with government support, are developing early electric vehicle markets. By 2015, 15 automakers produced over 10,000 plug-in electric vehicles per year, and five battery suppliers produced over 50,000 battery packs for plug-in electric vehicles per year. Many companies could increase their production volume to hundreds of thousands of electric vehicles per year in the 2020-2023 time frame. As a result, leading companies' battery pack costs would decrease to $150-$175 per kilowatt-hour in the 2020-2023 time frame.

The evolving market with next-generation electric vehicle technology will spur policy changes. The increased economies of scale with new battery packs are expected to dramatically reduce vehicle costs, up to $8,000 for a 120-mile battery electric vehicle, with the savings dependent on vehicle range and manufacturer volume. The decreased cost allows for a combination of longer electric range and more affordable electric vehicles, thereby addressing key adoption barriers and greatly broadening the electric vehicle market. These changes indicate that gradual tapering of government financial incentives targeted at reducing initial cost differences between conventional vehicles and electric vehicles over that time period could be warranted.

I. INTRODUCTION

The global electric vehicle market has been steadily expanding since 2010. Figure 1 shows annual electric vehicle sales globally from 2010 through 2015, with a breakdown by the 15 major automobile manufacturing groups with the greatest cumulative electric vehicle sales, based on Pontes (2016). Each company has over 20,000 cumulative electric vehicle sales, with the Renault-Nissan alliance highest with over 250,000 total global sales. The U.S. represents about 33%, Europe 31%, China 22%, and Japan 10% of the 1.2 million cumulative electric vehicle sales through 2015. As shown, the total annual electric vehicle sales surpassed milestones of 200,000 in 2013, 300,000 in 2014, and 500,000 in 2015. The cumulative sales of the 15 companies shown represent approximately 93% of global electric vehicle sales over the period.

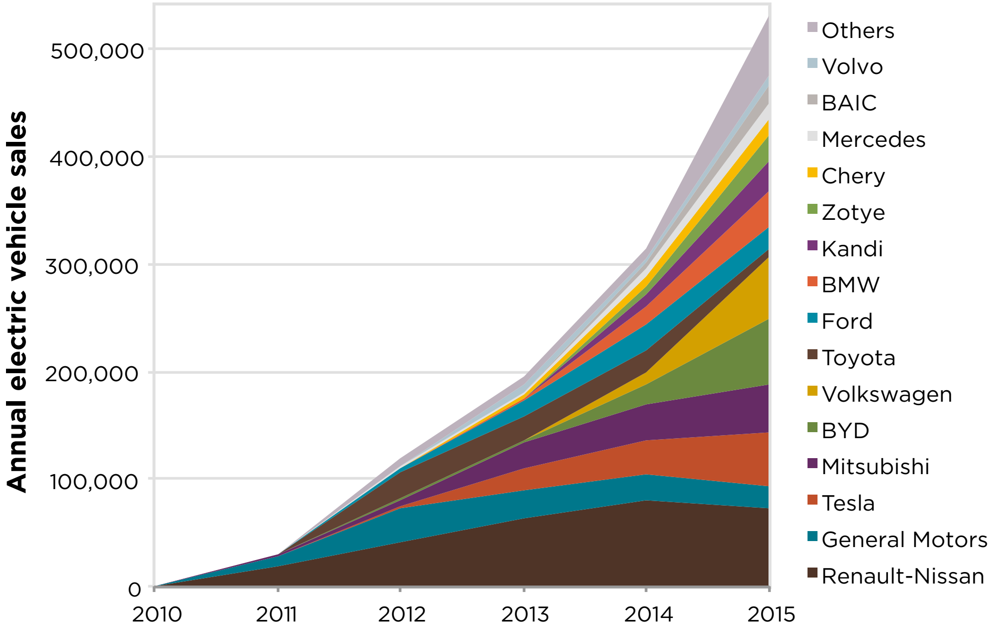

Figure 1. Annual electric vehicle sales globally through 2015

As electric vehicle technology continues to mature, manufacturers are striving to improve the performance of electric vehicles to better meet the demands of a broader set of consumers. Most electric vehicles sales globally are in markets with consumer incentives to defray the additional technology costs, as well as other supporting policy (Yang et al., 2016; Lutsey, 2015a). As of 2016, most major automobile companies already have introduced their first electric vehicle models into the marketplace and are well into the development of their next-generation technology.

This assessment examines the progress for five factors that relate to increased electric vehicle performance and consumer adoption. The metrics we analyze in this report include model availability, electric range, energy efficiency, battery production and cost, and electric vehicle production. In addition, this study examines what the next-generation battery developments and electric vehicle sales growth might mean for electric vehicle costs. Announcements from auto manufacturers indicate the steady progress of electric vehicle investments and technologies. Automobile manufacturers' electric vehicle investments are headed towards a greater diversity of models, increasing production volume, and increasing electric range for both plug-in hybrid electric vehicles (PHEVs) and full battery electric vehicles (BEVs), with each company charting a somewhat different path.

As detailed in the sections below, automobile manufacturer announcements indicate that substantial increases in the electric driving range and reductions in battery cost will be available in 2017 and 2018. Based on the expected electric vehicle battery advancements, companies are making a variety of bold projections about vehicle performance and the transition to higher production volumes. Some companies have announced plans for electric vehicle sales in the hundreds of thousands per year. Other companies have indicated that they will offer plug-in electric options on all their higher-volume platforms. Still others have announced that electric vehicles could account for 10%-25% of their vehicle sales in the 2020 to 2025 time frame.

In this paper, we examine these company developments in greater detail, including an analysis of sales data of existing models, research literature, and various projections of electric vehicle technology. This assessment analyzes the current and next-generation electric vehicle technologies in terms of the performance characteristics and costs of current and upcoming models. The scope of the analysis is global, including a collection of specifications of major passenger electric vehicle models in China, Europe, Japan, and the U.S. through 2015, as well as available data on models expected for sale in the following several model years. The analysis is based on a synthesis of public data from regulatory agencies, energy laboratories, academic research literature, and supplier and automobile company technical announcements. Based on these data, the work provides engineering analysis-based expectations for the evolution of the technology to inform policymakers assessing how best to sustain long-term electric vehicle market development.

II. ANALYSIS

This section includes a compilation and analysis of electric vehicle model availability, vehicle specification and performance data, and battery production volumes and costs. The vehicle specifications collected here are for available and announced electric vehicle models over the 2010-2016 time frame and include battery capacity, electric efficiency, and electric range. Data from both regulatory sources and auto manufacturer specification information are used for models through 2016. Battery costs are assessed based on the best available bottom-up engineering analyses. In addition, specifications for future model year electric vehicles are estimated based on available company announcements.

MODEL AVAILABILITY

The number of available electric vehicle models has increased greatly since 2010. Figure 2 displays the number of available models by vehicle class for calendar years 2010 through 2015. We note that some electric vehicle models with low sales volumes may have not been included if their sales were too low to show up in various datasets. As shown, there is now a global total of more than 100 electric vehicle models available in at least one major market. Only a handful of models are available on more than two continents. Examples of models that are substantially available on three continents are the Tesla Model S, Nissan Leaf, and BMW i3. Model availability in the U.S., Europe, and China has increased from about five each in 2011 to 25 or more in 2015. In the U.S. the distribution of model availability between BEVs and PHEVs has been about equal, whereas BEVs account for approximately three quarters of available electric vehicle models globally. Electric vehicles in various bus, medium-duty, and heavy-duty classes are excluded from this analysis. Although the global data indicate over 25 models were available in the three major regions in 2015, the models available in given regions and cities can be much lower (e.g., see Lutsey et al., 2015).

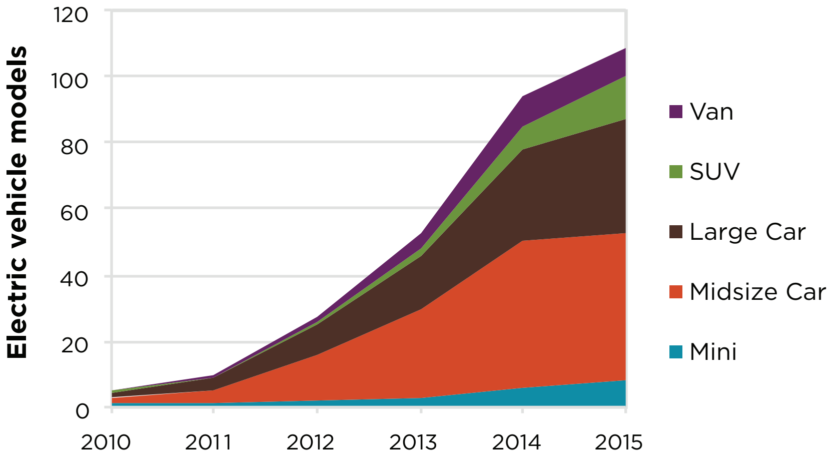

Figure 2. Electric vehicle model availability by vehicle class through 2015

As shown in Figure 2, the number of available models across all vehicle types has increased over the past five years. While large and midsize cars dominated the early electric-vehicle market, an increasing number of sport utility vehicles (SUVs), minivans, and crossovers have emerged since 2014. Lower-cost mini electric vehicles sales are also increasing. Not shown is the increasing number of electric vehicle models available with an all-wheel drive (AWD) option, up from two in 2014 to 11 in 2016.

Since 2010, the overall trend has been a steep increase in the number of electric vehicle models in each vehicle class (mini, midsize, large, SUV) and market. This trend is expected to continue. Many companies have announced they will greatly increase their electric vehicle model offerings in the future. BMW and Mercedes have indicated that they will offer plug-in electric options on all their higher volume models. For BMW this is about 13 models, for Mercedes, about 20 models (BMW, 2014; Sinclair, 2015). Volkswagen Group similarly announced plans to offer 20 all electric or plug-in hybrid models by 2020, up from just 5 in 2014 (Kable, 2016). Further, Volkswagen intends to expand its market reach by introducing 15 electric vehicles into the Chinese market by 2020 (Saeed, 2016). Volkswagen's luxury brand Bentley also has plans to offer PHEV versions of all future models (Karkafiris, 2016a).

ELECTRIC RANGE

Automakers continue to offer and sell electric vehicle models with greater all-electric range. Figure 3 shows both the increase in overall electric vehicle sales and the relative increase in sales of longer-range models since 2010. The trend reflects how sales of both BEVs (typically vehicles with a range of above 75 miles or 121 kilometers) and PHEVs (typically in the 20-75 mile, or 40-121 kilometer, electric-range category) are increasing. The electric range data shown in the figure are based on the U.S. combined city-highway test cycle, although electric ranges are compiled from each major market's particular test cycles. Vehicles' real-world energy consumption values tend to be substantially higher than their test-cycle values (Tietge et al., 2015). For comparison, the U.S. consumer-adjusted electric range is typically about 30% lower than the U.S. tested range reported (U.S. EPA, 2016). For vehicle models that are available exclusively in Europe, China, or Japan markets (i.e., not tested in the U.S.), vehicle range on the New European Driving Cycle (NEDC) and Japan's JC08 Cycle are obtained from regulatory agencies and official manufacturer websites and are then normalized to the U.S. test cycle based on best available data.

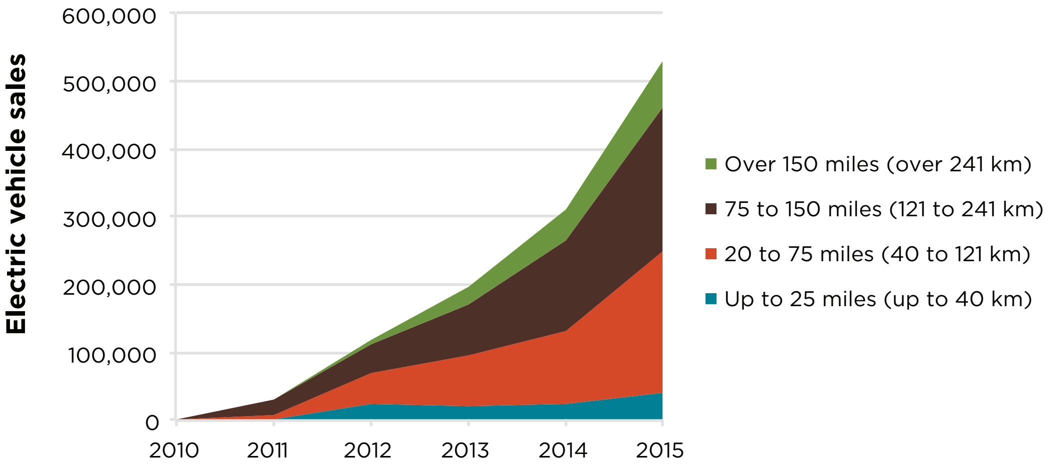

Figure 3. 2010-2015 annual electric vehicle sales by electric vehicle range

Automakers have announced that many 2016-2018 models will see greatly increased electric vehicle range. Examples include 20%-50% increases in electric range for Nissan Leaf, Volkswagen e-Golf, Chevrolet Volt, and BMW i3 models (Bruce, 2016; Kurylko, 2016; Brown, 2016; Nissan, 2016; Chevrolet, 2016a). Notably, General Motors (GM) has announced that the new Chevrolet Bolt will have a range of 200 miles, or about 322 kilometers (Chevrolet, 2016b). Announcements by Nissan, Mercedes-Benz, Porsche, and Audi indicate 200-mile, and potentially up to 300-mile, range vehicles could reach the market soon (Chappell, 2015; Hetzner, 2015; Porsche, 2015; Lambert, 2015). Similarly, Volkswagen announced a concept Budd-e model that is capable of over 200 miles per charge and may become available around 2019 (Volkswagen, 2016). Tesla begun manufacturing a 265-mile-range electric luxury vehicle in 2012, and has announced a 215-mile electric vehicle at a more mainstream price point (Musk & Straubel, 2012; Tesla Motors, 2016a).

Figure 4 displays changes in several popular electric vehicle models' electric range in the 2013-2016 time frame and estimated range improvements for 2016-2018, based on manufacturer announcements. For the vehicle models shown, as above, the range is given as the U.S. test cycle range. The announced 200-mile range of the model year 2017 all-electric Chevrolet Bolt is assumed to be the consumer label range, which is likely to be 30% lower than the test-cycle range, based on existing data on electric vehicles in the U.S. The Chevrolet Bolt's announced 200-mile range is nearly two and a half times that of the 2015 Chevrolet Spark's 82-mile range. Also shown in the figure is the expected increase in electric range from several other models, including the anticipated next-generation Nissan Leaf that is expected by 2018. We emphasize that the official electric range values are not yet known, so the future range values are illustrative.

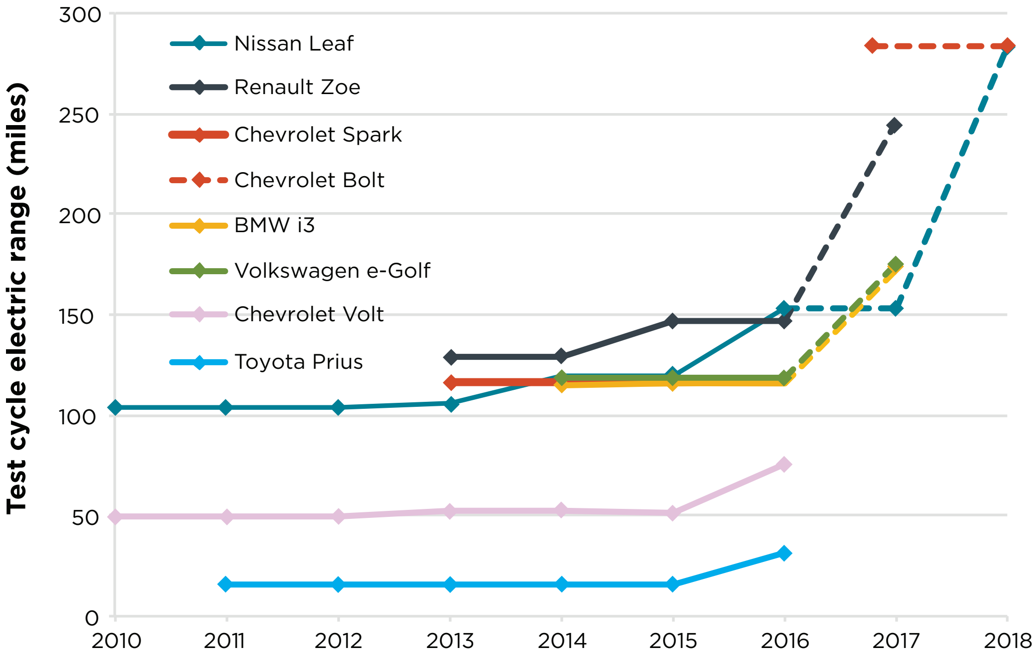

Figure 4. Electric vehicle range for popular 2010-2016 models, and announced 2017-2018 range

PHEVs are also expected to see increased electric range, leading to the potential for an increased percentage of driving that is powered by electricity. As shown in Figure 4, the 2016 Chevrolet Volt saw a 43% increase in range, from about 52 miles (37 miles on consumer label) to 75 miles (53 miles on consumer label) from the previous model. The recently announced next-generation Toyota Prius Prime plug-in hybrid will come with double the all-electric range and battery capacity (from 4.4 kWh to 8.8 kWh) and is expected to launch in late 2016 (Toyota, 2016). Not shown in the figure is Honda's next-generation PHEV, which is expected to have more than triple the range of the 2014 Accord PHEV and is expected in 2018 (Lassa, 2015). BMW and Mercedes-Benz have also announced major improvements in the next-generation electric range of their available PHEV models. Both manufacturers have indicated increasing their vehicles' electric range from about 15 miles to 62 miles (Boeriu, 2014; Motoring, 2016).

ELECTRIC VEHICLE EFFICIENCY

One of the enablers for increased vehicle range is improving electric vehicle efficiency. It is expected that efficiency will continue to increase with advancements in powertrain efficiency, power electronics, aerodynamics, and lightweighting technologies. A number of emerging models use one or more of these strategies to boost vehicle efficiency. Through its partnership with LG Chem, GM achieved notable advancements in electric vehicle battery technology, as demonstrated by the 2016 Chevrolet Volt. Through improvements in individual cell capacity, GM has decreased the cell count in the Volt by 33% while simultaneously increasing its total capacity by about 8% to 18.4 kWh. As a result, GM estimates that the 2016 Volt is 100 pounds lighter and 12% more efficient (General Motors, 2015).

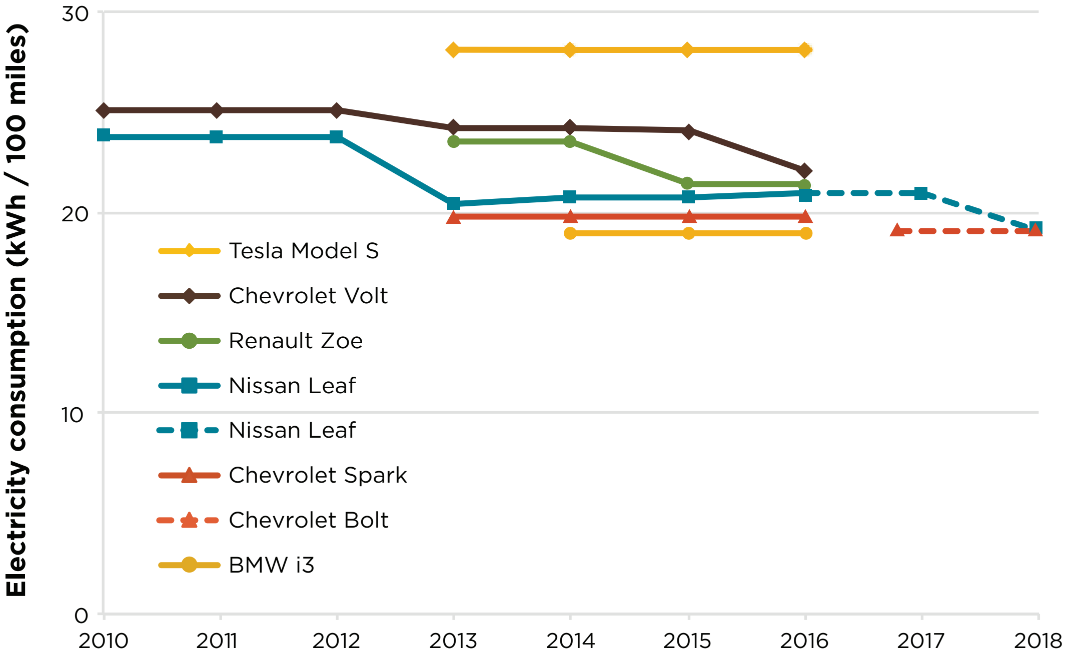

Figure 5. Electric vehicle efficiency improvements

Figure 5 illustrates recent and announced efficiency improvements, based on electricity consumption on the U.S. combined regulatory test cycle based on U.S. EPA data (2016). Consumer-adjusted energy consumption, accounting for real-world driving efficiency values, is about 40% higher than the values shown. The figure highlights the efficiency improvement of the Nissan Leaf between 2012 and 2013 of nearly 14%, which

Nissan attributes to refined aerodynamics, greater utilization of regenerative braking, and better energy management (Nissan, 2013). Further efficiency improvements are anticipated in the 2018 model, possibly from improved electric motor efficiency and greater use of lightweight materials (Motoring, 2015). Similarly, Renault has made significant efficiency improvements to the Zoe between the 2014 and 2015 models. Renault's greater use of lightweight materials and improved electronic management resulted in a reduction of energy use of approximately 9% (Renault, 2015). Figure 5 also shows the BMW i3 as having the lowest electricity consumption per distance traveled, which is largely attributed use of lightweight materials such as aluminum and carbon fiber-reinforced polymers and advanced aerodynamics (BMW 2016a, 2016b).

BATTERY TECHNOLOGY, PRODUCTION, AND COSTS

Manufacturers are both increasing battery pack energy capacity and selling more vehicles with higher capacity batteries. Figure 6 shows the growth in the annual deployment of electric vehicle battery capacity for given ranges of battery capacity. Based on our analysis here, in new 2015 vehicles, the total plug-in electric vehicle battery capacity was approximately 12 gigawatt-hours (GWh). The cumulative global battery capacity from these 2010-2015 vehicles is about 25 GWh. As shown, much of the growth in total battery pack energy capacity is in larger battery packs. The over-40-kWh pack segment increased from nearly zero in 2012 to 12% of overall electric vehicle sales in 2015, due to Tesla sales with battery packs of 60 kWh or higher. Overall, the sales-weighted average battery pack increased from 17.7 kWh in rated battery capacity in 2012 to 22.4 kWh in 2015. The average BEV battery pack was rated as 30 kWh, compared to an average rated PHEV pack of 12 kWh for all 2015 electric vehicles sold globally.

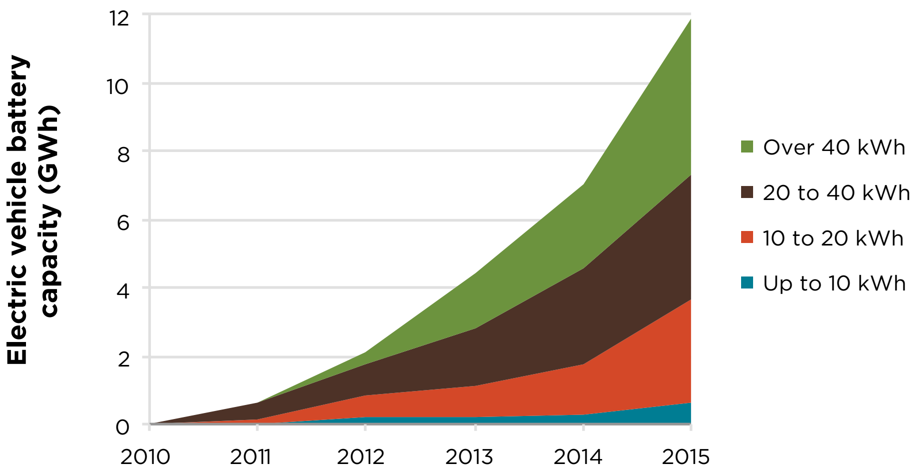

Figure 6. Additional battery capacity deployed, by electric vehicle battery pack size, 2010-2015

The continuing transition to battery packs with greater energy capacity is expected to come from more energy-dense lithium-ion batteries that incorporate battery chemistry, design, and manufacturing improvements. These types of battery improvements allow for increased energy capacity with much less weight and volume than would result from a bigger pack with more cells of the same technology. For example, the 2017 e-Golf is expected to see a 32% increase in cell energy density, leading to a 30% to 50% increase in range for the same size battery pack (Bruce, 2016; Brown, 2016). The 2017 Bolt, as discussed above, will at least double the capacity of the 21 kWh Chevrolet

Spark predecessor with its 50 kWh pack despite similar volume and mass due to all the battery pack improvements. The 2018 Nissan Leaf is expected to offer a similar jump from the 24 kWh 2015 Nissan Leaf. In addition, many 2010-2012 packs initially used more conservative designs that reduced performance in exchange for higher safety factors; greater experience and improved design are increasing the fraction of the battery pack that is useable.

Some of these improvements are related to battery chemistry, in particular the cathode and anode materials. The battery packs use several different lithium-ion battery types, generally distinguished by the cathode material. Among the main types are 18650 nickel cobalt aluminum (NCA) cells in the Panasonic-Tesla packs, lithium manganese oxide (LMO) in Nissan's 2015 packs, and lithium iron phosphate types that are more common in the China market. These battery chemistries are typically shifting toward higher density nickel cobalt manganese (NCM) cells for Panasonic-Tesla in 18650 form and NCM in pouch form for others such as General Motors-LG Chem (Anderman 2014, 2016b). The cell materials, manufacturing process, cost, and manufacturing scale are key factors that determine automobile companies' choices of battery packs. The battery supply chain is becoming more competitive, with some auto companies choosing multiple suppliers globally, and some battery companies supplying packs for multiple automakers.

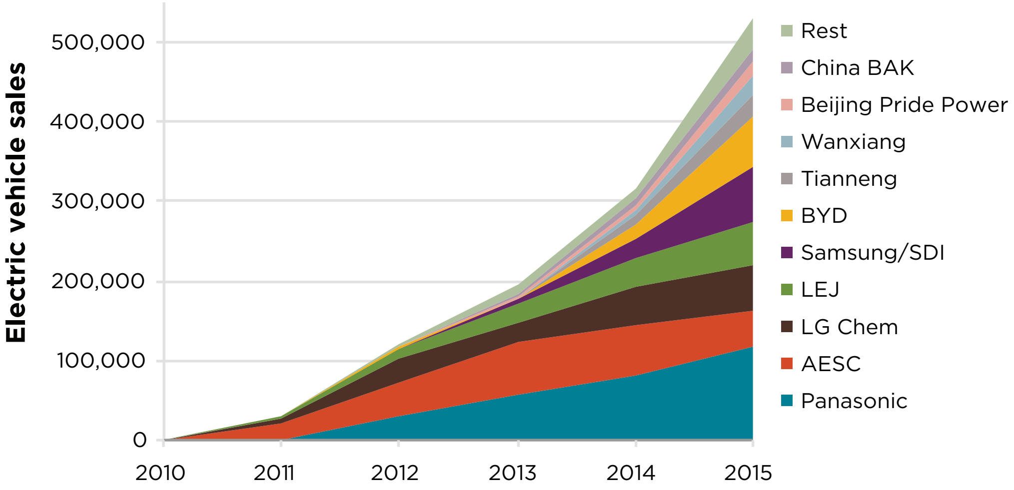

Figure 7. Electric vehicle sales by battery supplier

Examination of electric vehicle trends from the battery supplier perspective provides further details on the company-specific growth into larger production volume. Figure 7 shows the same electric vehicle sales growth trend as shown in Figure 1, but instead by battery supplier. The 10 supplier company groups shown represent about 94% of cumulative 2010-2015 plug-in electric passenger vehicles. The figure shows the leading battery suppliers that are achieving greater battery pack production scale, with Panasonic at over 115,000 vehicles, and the next five suppliers at 45,000 to 70,000 vehicles per year in 2015. The larger-volume battery suppliers are providing battery packs to several vehicle manufacturers. For example, Panasonic batteries are used in Ford, Tesla, Toyota, and Volkswagen vehicles. LG Chem batteries are used in GM, Ford, Hyundai, and Renault electric vehicles. AESC is the partnership between Nissan and NEC, and LEJ production is mostly for Mitsubishi's electric vehicles. Companies with the highest 2014-2015 growth in automotive battery packs include Samsung/SDI, BYD, Tianneng, Wanxiang, and Beijing Pride Power (BAIC). The partnerships between vehicle manufacturers and battery suppliers are more complex than can be discussed and represented in the figure.

Several studies have analyzed the detailed battery pack production costs of various battery types in addition to how costs vary at different production volumes. The studies indicate that as the market becomes more mature and competitive, production volume is a key factor in battery pack cost. Figure 8 shows estimates for battery cost production at a given plant, based on key factors of battery type, manufacturing process, and production volume, based on Anderman (2014, 2016a, 2016b) and Nelson et al. (2015). The battery types shown are LMO (like many 2011-2014 models in the U.S. and Europe), NMC (like the upcoming Chevrolet Bolt with LG Chem batteries), and 18650 (like the Panasonic-Tesla current and expected next-generation batteries). The figure shows that battery pack production at 2015 levels, typically at 10,000 to 30,000 units per year, is approximately $300/kWh. However, much larger production volumes of over 200,000 battery packs per year would equate to $200/kWh or less, whereas production volumes of less than 10,000 packs per year would equate to $400/kWh or more. Volumes of 400,000 to 500,000 packs per year, with Panasonic-type 18650 packs or LG Chem-type NMC pouch packs, are estimated at $145 to $175 per kWh for battery electric vehicle packs.

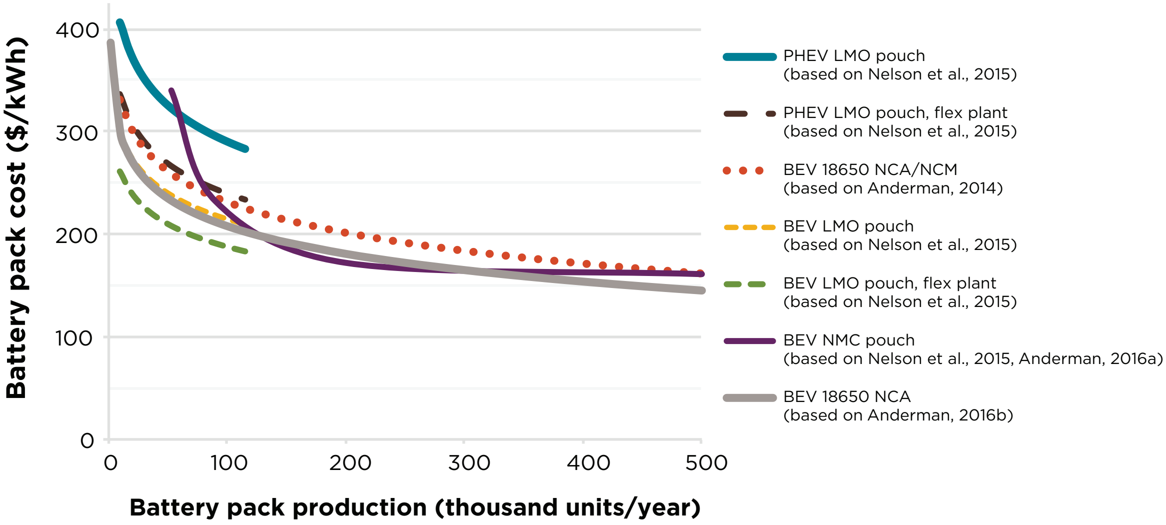

Figure 8. Battery pack cost at given annual production volume for various battery electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV) battery types

Several additional points help put Figure 8 in context. Comparing the Nelson et al. (2015) LMO pouch results, the figure shows the value of using a "flex plant" as compared to a dedicated plant. The Nelson et al. results indicate that using a flex plant to produce a combination of cells for BEV, PHEV, and non-plug-in hybrid packs can reduce the relative pouch costs, due to the greater overall manufacturing scale. This may be important as several companies are jointly pursuing hybrid and plug-in electric vehicle production strategies, and this could be an effective way to reduce costs without committing to such large production volumes for a single drivetrain. Hyundai and Honda, for example, have created vehicle platforms capable of supporting multiple powertrain choices and thus may use the flex-plant approach (Hyundai, 2016; Honda, 2015).

We emphasize that these are engineering-based cost estimates that could be considered conservative as compared to other estimates. These cost projections are based on known chemistries and relatively well-understood battery manufacturing processes being scaled up. Although these are based on the best available bottom-up battery manufacturing studies, it is likely that future technology will offer lower costs still. The U.S. Department of Energy and others are analyzing continuing battery innovation with a target of $125/kWh for 2022 (Faguy, 2015), and many of the battery suppliers and automobile manufacturing companies are also working toward battery performance advancements and cost reductions.

VEHICLE PRODUCTION AND COST IMPACTS

Greater battery production volume, as illustrated above, is a key determinant to increasing electric vehicles' competitiveness with conventional vehicles over time. To better understand the potential shift to higher volume, lower cost batteries, we analyze a hypothetical scenario for increased electric vehicle production. This section assesses 2015 electric vehicle deployment by manufacturer and develops a hypothetical future sales volume scenario through 2023. This potential scenario is based on each company's 2014-2015 electric vehicle sales growth, 2015 sales volume, and our judgment regarding automaker announcements related to electric vehicle investments and future production targets. The hypothetical increase in vehicle production is linked with battery cost-versus-volume assumptions in the section above to estimate future battery pack cost implications.

Figure 9 shows the 2014 and 2015 electric vehicle sales by automobile group. As illustrated, companies tended to move to greater annual production volume in 2015, some with much greater annual increases. Renault-Nissan, BYD, Volkswagen, Tesla, and Mitsubishi each sold over 40,000 units in 2015. Companies such as BYD, Volkswagen, Zotye, BAIC, JAC, SAIC, Hyundai, Fiat, and Zhidou have more than tripled their electric vehicle sales volume from 2014 to 2015. Despite this promising growth, the sale of electric vehicles for most of these companies (with the exception of Tesla) is below 2% of their total sales, highlighting the challenge of scaling up electric vehicle production. Overall, the 20 companies shown represent over 97% of global 2015 electric vehicle sales.

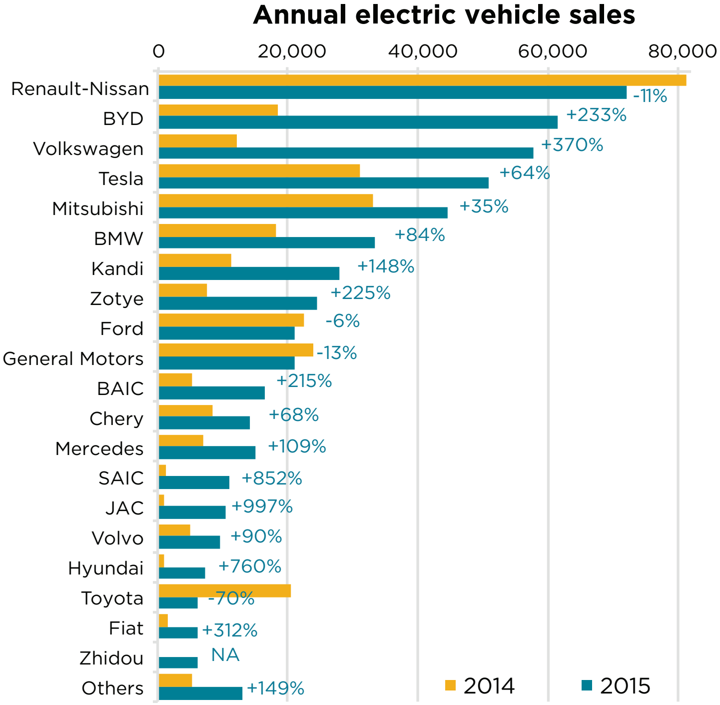

Figure 9. Global annual electric vehicle sales by company in 2014 and 2015

To assess the further evolution of battery pack costs, we develop a scenario for growth in electric vehicle production and sales. We emphasize that this is an illustrative scenario and that electric vehicle production estimates such as this are highly uncertain. In the process, we assess a potential scenario for the future increase in electric vehicle sales by company. These company-specific sales are linked to the battery pack cost estimates in the previous section to estimate future battery pack costs. Due to the inherent uncertainty in such an exercise, we bin companies by their historical sales volume; however, this analysis is in no way meant as a projection of relative market success of these particular manufacturing companies.

Table 1 summarizes key assumptions for this analysis' illustrative scenario for increased global electric vehicle sales, based on average company-specific electric vehicles sales. To summarize a hypothetical future scenario with a progression to higher volume, but without specifically making forecasts on particular company sales, companies were grouped into three categories. "High volume" electric vehicle companies are assumed to increase sales from an average of about 60,000 in 2015 to an average of 380,000 (range of 300,000 to 450,000) vehicles per year in 2023. "Medium volume" companies include those that could increase from an average of 15,000 electric vehicle sales in 2015 to 110,000 vehicles per year in 2023. The 30 remaining electric vehicle manufacturing companies were assumed to increase from an average of 1,000 in 2015 to about 30,000 vehicles per year in 2023. Based on a simple judgment from Figure 9 and the positioning of companies, we assumed that there would be five companies in the high volume group, 15 in the medium volume group, and another 30 companies in the remaining group. Under this scenario, on average, the medium volume companies lag the leading companies by about 5 to 7 years, and the remaining companies are about 5 to 7 years further delayed in terms of annual electric vehicle production.

Table 1. Summary scenario assumptions for average annual electric vehicle sales by manufacturer group, and global electric vehicle sales volume for 2015, 2020, and 2023

	High volume companies	**Medium volume companies**	**Remaining companies**
Potential example automaker groups	BYD, Mitsubishi, Renault-Nissan, Tesla, Volkswagen	BAIC, BMW, Chery, Daimler, Fiat, Ford, General Motors, Hyundai, JAC, Kandi, SAIC, Toyota, Volvo, Zhidou, Zotye	Citröen, Mahindra, Mazda, Peugeot, Subaru, Suzuki, Tata, etc.
Estimated number of major companies	5	15	30
2015 sales	60,000	15,000	1,000
2020 sales	250,000	50,000	10,000
2023 sales	380,000	110,000	30,000

Numbers in the table are rounded

Global electric vehicle sales in this scenario increase from approximately 530,000 in 2015 to approximately 4.4 million in 2023. To provide context for the sales growth scenario in Table 1, the sales are assessed in terms of the annual growth rate and the percentage of total sales shares in future years. The associated annual company-specific growth rates for this scenario of the electric vehicle market are 34% for 2015-2020 and 24% for 2020-2023. Many companies far exceeded these growth rates, as seen in the 2014 versus 2015 sales snapshot depicted in Figure 9. Overall, assuming the global vehicle market grows at 3% per year, the 2.3 million electric vehicle sales is likely to account for about 3% of global vehicle sales in 2020, and the 4.4 million electric vehicle sales in 2023 would be about 5% of total global vehicle sales.

This increased deployment of future electric vehicle sales is slower than the announced plans of several major companies and many government projections. In terms of sales share, for major global companies in the high volume group (e.g., Renault-Nissan or Volkswagen), assumed electric vehicle sales of around 380,000 could be approximately 2%-3% of these major companies' annual vehicle sales in 2023. Mercedes announced an annual sales target of 100,000 per year by 2020. Companies such as Audi, Mitsubishi, Renault-Nissan, and Volvo have announced that electric vehicles could account for 10%-20% of sales in 2020 or up to 25% of their vehicle sales in 2025 (Lambert, 2015; Mitsubishi, 2011; "Mr Ghosn bets the company," 2009; Korosec, 2015; Sheehan, 2016). Tesla has forecast an increase in its production to 500,000 in 2018, compared to 50,000 in 2015, as it moves to a higher-volume mainstream market car (Randall, 2015; Hull, 2016). BYD plans to ramp up battery and electric vehicle production volume to about 500,000 vehicles in 2020 (Groom, 2015). Battery supplier LG Chem also has plans to increase battery production at its Nanjing mega plant to support 200,000 BEVs (or 700,000 PHEVs) annually by 2020 (Yoo-chul, 2015). Volkswagen has announced an annual sales target of 2 to 3 million electric vehicles, equivalent to 20%-25% of its global sales, by 2025 (Volkswagen Group, 2016). This context is added to emphasize that, although the increased volume projections are much larger than 2015 sales, the overall scenario is quite conservative compared to many manufacturer announcements as well as other analyses of the potential increase in global electric vehicle sales based on government targets. Several such scenarios have been summarized by Lutsey (2015a, 2015b).

Based on the assumptions outlined, Figure 10 summarizes the vehicle production increase, from Table 1, and the associated battery pack cost based on Figure 8 for 2015 through 2023. As shown, as global annual electric vehicle sales increase from half a million in 2015 to over 4 million in 2023, battery pack costs decrease to $150-$175 per kWh for high volume electric-vehicle-producing companies in 2023, and to about $175-$225 per kWh for medium volume companies that lag the leading companies by 5 to 7 years. There is substantial uncertainty about which companies will reach higher volume by given future years. This assessment provides a reasonable estimate for the range of battery supplier's competition and scale to meet plausible future growth projections for auto manufacturing companies. These battery cost estimates are based on the cost-per-kilowatt hour projections of Anderman (2014, 2016a, 2016b) and Nelson et al. (2015), as well as the assumed vehicle production levels of the high volume and medium volume manufacturers, as discussed above. The other companies that start at lower volume electric vehicle sales are not separately estimated; these companies could gain from partnerships with higher volume automobile or battery supplier companies that are within the high or medium volume cost regions shown in the figure.

A few points help put Figure 10 in context. Here we assess future battery pack costs by linking a potential future production volume scenario with the battery cost estimates in Figure 8. This future production volume scenario is based on auto manufacturer vehicle deployment. Alternatively, a scenario based on battery supplier production volume may result in higher volumes and lower costs, as multiple manufacturers may purchase battery packs from the same supplier (e.g., General Motors, Ford, Hyundai, and Renault purchase battery packs from LG Chem). As demand for battery packs grows, battery suppliers may develop increasingly larger production facilities and continue to reach lower costs (e.g., Sedgwick, 2015; Karkafiris, 2016b; Yoo-chul, 2015).

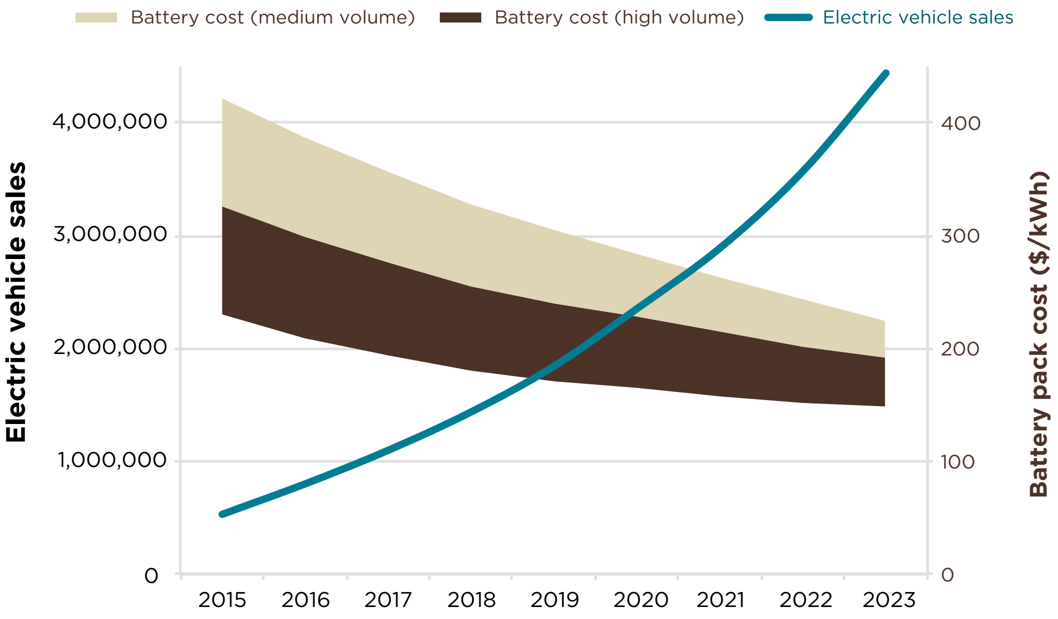

Figure 10. Scenario for estimated electric vehicle sales and battery pack cost

The cost curves in Figure 10 are based on BEV battery pack production volume. For companies that manufacturer primarily for PHEVs, the cost per kWh would remain higher. Based on the previously cited Anderman and Nelson studies, PHEV per kilowatt-hour battery pack costs tend to be greater than those of BEVs by approximately 30% to 60% for similar battery pack production volumes. This is due to the fact that many of the PHEV battery pack systems (e.g., battery management, disconnect, thermal management) do not scale up with energy capacity like battery cell materials do. Another reason for this is that PHEVs have higher power-to-energy ratios, and this can require more expensive materials.

The 2015 battery cost results from this analysis approximately match estimates found elsewhere. Nykvist and Nilsson (2015) indicated that the industry was at about $400/kWh and market leaders such as Nissan and Tesla had battery costs of approximately $300/kWh in 2014. The current and future-year estimates also approximately match numbers announced by various automakers. Audi has announced reaching costs as low as $250/kWh in 2015 (Beene, 2015). Tesla Motors estimates that economies of scale could decrease its battery manufacturing cost by more than 30% (Tesla Motors, 2016b), though some outside analysts have argued that cost reductions from the 35 GWh per year factory could exceed 50% and possibly achieve $125/kWh (Shallenberger, 2015). The findings here are also in line with a comprehensive literature review of electric vehicle costs by Wolfram and Lutsey (2016). These numbers are also broadly consistent with GM's statements about reducing battery cost at the cell level to $145/kWh in 2016 and $100/kWh 2020 as it ramps up its next-generation Chevrolet Bolt deployment (King, 2015). The research cited above indicates these cell-level data approximately match the pack level results presented here, as battery cell-level costs are typically 20-40% lower than battery pack-level per-kWh costs (e.g., see Anderman, 2016b).

Based on the battery pack cost reductions indicated from the above assessment of increasing vehicle production volume, the impacts on battery vehicle costs on a per-vehicle basis are provided for a few simplified illustrative cases. As a starting point, we consider a battery electric vehicle pack of 34 kWh with a consumer range of 120 miles. The battery cost improvement from an industry-average of $400/kWh in 2015 to next-generation technology at $200/kWh or less can be considered in different combinations of cost reduction and/or increased electric range. For example, without increasing vehicle range, that 120-mile range BEV would see a cost reduction of $7,600 (at $175/kWh) or $8,500 (at $150/kWh). Alternatively, by improving vehicle specifications to 57 kWh and 200 miles (for battery capacity and range), the vehicle would see a $3,700 to $5,100 cost reduction (for $175/kWh and $150/kWh).

From this basic calculation, it is evident that options for some combination of cost reduction and increased range are approaching. From the industry announcements summarized above, automakers could take different approaches that provide more options for differing customer demands for lower cost and increased range. For example, the full cost reduction of $8,000 or more would be more desirable for many applications that do not need additional range, such as households or fleets with low daily vehicle use and customers with widely available charging at home, work, and public locations. On the other hand, the same next-generation battery technology could increase range to up to 200-mile real-world range, but with a smaller associated cost reduction, up to about $5,000, due to the larger battery pack. This alternative would be more desirable for customers needing greater daily range or with greater charging constraints.

These are meant as illustrative basic calculations to show the automakers' dilemma in using technology improvements to address the consumer barriers of cost and range. Of course, the actual electric vehicle cost reductions are battery-supplier-specific and automaker-specific, and also would gain from a more complete accounting of all the other electric vehicle technology improvements (e.g., motors, power electronics) as discussed by Wolfram and Lutsey (2016). As indicated above, companies that start from lower volume (e.g., less than 10,000 electric vehicles per year in 2015) and higher battery pack costs (e.g., more than $400 per kWh) would likely realize much greater per-vehicle cost reductions in the 2020 time frame. Conversely, the high volume 2015 electric vehicle manufacturing companies that are currently closer to $200/kWh and already have realized significant per-vehicle cost reductions would likely have the lowest absolute battery pack costs, but would likely see lower cost-per-vehicle reductions compared to lower-volume companies. As reflected in Figure 10, as the rate of battery cost reductions slows with increasing production volume, the cost gap between medium and high volume companies decreases. This could further influence the price of electric vehicles, as greater competition drives manufacturers to continue to address key consumer adoption barriers and offer models with greater performance and reduced cost. These cost estimates are based on known lithium-ion chemistries. More advanced, in-development battery technologies with other chemistries could allow lower costs and greater range.

Based on this analysis, the positive trends toward greater electric vehicle model availability, lower cost, longer range, and higher production volume are expected to continue. Markets with the highest electric vehicle market development are beginning to move beyond early adopters, and governments could be pushed to respond in several ways. Financial and non-financial incentives may have to evolve in ways to reflect the technology progress of more electric vehicle sales, generally with lower cost and greater electric range. In the U.S., for example, the federal income tax credit includes a phaseout clause within the policy that phases down after a manufacturer sells 200,000 eligible plug-in electric vehicles. Other governments are considering their own approaches to phase out incentives through the transition to higher volume. These trends would signal the increased competitiveness of electric vehicles with conventionally fueled vehicles from a cost and performance perspective. This could then indicate the decreased need for governments to bridge the cost difference between the two technologies. An important discussion for future policymaking is when and how to appropriately taper electric vehicle incentives to match these trends without compromising consumer adoption.

III. CONCLUSIONS

This research uses a combination of electric vehicle sales data, vehicle specifications, academic research literature, and recent manufacturer announcements to assess the progress of electric vehicle technology improvements along a variety of metrics related to vehicle performance and market adoption. Based on our analysis, we find that several key performance metrics, such as electric vehicle range and battery capacity, not only have been steadily improving since 2010, but also are poised to dramatically increase in the next 5 years as the next-generation technology develops. With technology advancements, automakers are improving electric vehicle performance characteristics, expanding the variety of models on the market, and reaching greater economies of scale as production ramps up. Together, these trends indicate an evolving electric vehicle market that is increasingly overcoming key consumer performance and cost adoption barriers.

The analysis of battery manufacturing costs is based on studies of known lithium-ion battery chemistries. The analysis is based on a synthesis of best-available bottom-up engineering studies in order to provide reasonable expectations for the evolution of the technology, supply chains, and consumer market development. The electric vehicle sales in this study, both on a per-company and overall industry basis, are grounded by average annual vehicle growth rates of approximately 30% per year. As a result, the scenario used in this analysis amounts to approximately 5% of global vehicle sales being plug-in electric vehicles in the 2023 time frame. In a number of cases, there are auto companies that have announced projected electric vehicle updates that are greater than the scenario analyzed here. In addition, partnerships between automobile companies and consolidation among the major battery supplier companies could drive battery pack costs down more than estimated in this analysis.

Based on our analysis, we draw the following conclusions regarding electric vehicle models, electric vehicle range, cost reductions, and possible policy implications. First, increased diversity of electric vehicle models is creating more alternatives across all market segments. Manufacturers are increasingly offering all-electric or plug-in hybrid models in most vehicle classes. Over 25 different plug-in electric models were offered in 2015 in the three largest national markets of China, Europe, and the U.S. Increasingly these models are being made available in more local markets within the three major regions, as well as globally. An assortment of plug-in options for smaller cars, sedans, crossover sport-utility vehicles, low cost brands, luxury brands, and models with all-wheel drive, are more broadly meeting consumer demands. This proliferation and wider deployment of electric models is a prerequisite to growing the market.

In addition to the expanded offerings, major technology changes are underway. Electric vehicles with increased electric range are entering the market from 2016 to 2018. Battery technology advancements and greater production volume are allowing companies to offer electric vehicles with improved performance and range. More vehicles with greater battery capacity, electric efficiency, and range have been sold in steadily larger numbers through 2015. Announced next-generation Chevrolet, Nissan, and Tesla models indicate mass-market cars with at least 200 miles (over 320 kilometers) of electric range will accelerate this trend. This is happening while companies are making the move to higher production and lower cost**.** Vehicle and battery manufacturers, with government support, are developing early electric vehicle markets. By 2015, 15 automakers produced over 10,000 plug-in electric vehicles per year, and five battery suppliers produced over 50,000 battery packs for plug-in electric vehicles per year. Many companies could increase their production volume to hundreds of thousands of electric vehicles per year in the 2020-2023 time frame. As a result, leading companies' battery pack costs would decrease to $150-$175 per kilowatt-hour in the 2020-2023 time frame.

With all these market and technology shifts, the evolving and growing market will spur policy changes. The increased economies of scale with new battery packs are expected to dramatically reduce vehicle costs, with the savings dependent on vehicle range and manufacturer volume. The decreased cost allows for a combination of longer electric range and more affordable electric vehicles, thereby addressing key adoption barriers and greatly broadening the electric vehicle market. These changes indicate that gradual tapering of government financial incentives targeted at reducing initial cost differences between conventional vehicles and electric vehicles over that time period could be warranted.

In addition to the conclusions above, we also find a number of areas that were beyond the scope of this paper warrant further investigation. As electric vehicle models proliferate and their sales increase, leading global markets could see mass-market adoption of electric vehicles. Expanded infrastructure for home, workplace, and public rapid charging will likely be needed to match this deployment. Electric power utilities' support for charging infrastructure might become increasingly important, as would campaigns to increase awareness and educate consumers (e.g., see National Research Council, 2015).

The implications of this research are broad. Governments around the world are seeking to accelerate the electric vehicle market (Lutsey, 2015a). This analysis indicates several positive trends in greater model availability, lower cost, longer range, and higher production volume of electric vehicles and battery packs. These trends may have implications on the design of policies and incentives that are intended to promote electric vehicle uptake. Just as this work highlights reasons for great enthusiasm for electric vehicle technology, it also points to reasons to temper that enthusiasm to a longer-term outlook. The technology, market, and supply chain trends related to electric vehicle market development will require many years of steady investment, as well as sustained policy support through the transition.

REFERENCES

Anderman, M. (2014). The Tesla battery report: Tesla Motors: Battery technology, analysis of the Gigafactory, and the automakers' perspectives. Retrieved from http://doc.xueqiu.com/1493d8803372d3fd67cb5c51.pdf

Anderman, M. (2016a). The xEV Industry Insider Report. Retrieved from http://www.totalbatteryconsulting.com/industry-reports/xEV-report/Extract-from-the-xEV-Industry-Report.pdf

Anderman, M. (2016b). The Tesla battery report: Tesla Motors: Battery technology, analysis of the Gigafactory and Model 3, and the automakers' perspectives. Retrieved from http://www.totalbatteryconsulting.com/industry-reports/Tesla-report/Extract-from-the-Tesla-Battery-Report.pdf

Beene, R. (2015, November 1). Audi's A3 e-tron to pave way for electrified vehicle push. *Automotive News*. Retrieved from http://www.autonews.com/article/20151101/OEM05/311029960

BMW. (2014, January 12). New generation of plug-in hybrid models. Retrieved from https://www.press.bmwgroup.com/global/pressDetail.html?title=new-generation-of-plug-in-hybrid-models&outputChannelId=6&id=T0197302EN&left_menu_item=node__803

BMW. (2016a). Emission-free into the future. Sustainability and BMW i. Retrieved from http://www.bmw.com/com/en/insights/corporation/bmwi/sustainability.html

BMW. (2016b). The first-ever, all-electric BMW i3. Now available at BMW of San Diego. Retrieved from http://www.bmwofsandiego.com/new-bmw-i3.aspx

Boeriu, H. (2014, November 27). The future of BMW plug-in hybrids is exciting. BMWBlog. Retrieved from http://www.bmwblog.com/2014/11/27/future-bmw-plug-hybrids-exciting/

Brown, S. (2016, May 23). Volkswagen's e-Golf to get battery boast to 35 kWh. DriveEV Retrieved from https://driveev.net/2016/05/23/volkswagens-e-golf-to-get-battery-boast-to-35kwh/

Bruce, C. (2016, January 9). VW e-Golf will get 30% range boost thanks to improved batteries. AutoBlog Retrieved from http://www.autoblog.com/2016/01/09/volkswagen-e-golf-30-percent-range-increase-new-batteries/

Chappell, L. (2015, November 16). Next-gen Leaf: More tech despite low sales. *Automotive News*. Retrieved from http://www.autonews.com/article/20151116/OEM05/311169970/next-gen-leaf-more-tech-despite-low-sales

Chevrolet. (2016a). Chevrolet: 2016 Volt. Retrieved from http://www.chevrolet.com/2016-volt-electric-car.html

Chevrolet. (2016b, January 11). Drive unit and battery at the heart of Chevrolet Bolt EV. Retrieved from http://media.chevrolet.com/media/us/en/chevrolet/home.detail.html/content/Pages/news/us/en/2016/Jan/naias/chevy/0111-bolt-du.html

Faguy, P. (2015, June 8). *Overview of the DOE Advanced Battery R&D Program*. Retrieved from United States Department of Energy website: http://energy.gov/sites/prod/files/2015/06/f23/es000_faguy_2015_o.pdf

General Motors. (2015, January 12). Chevrolet introduces all-new 2016 Volt. Retrieved from http://media.gm.com/media/us/en/gm/news.detail.html/content/Pages/news/us/en/2015/Jan/naias/chevrolet/volt/0112-volt-2016-intro.html

Groom, N. (2015, March 13). China's BYD takes aim at Tesla in battery factory race. Reuters. Retrieved from http://www.reuters.com/article/us-byd-battery-idUSKBN0M92MZ20150313

Hetzner, C. (2015, September 3). Mercedes is working on Tesla Model S fighter, r&d chief tells paper. *Automotive News Europe.* Retrieved from http://europe.autonews.com/article/20150903/ANE/150909947/mercedes-is-working-on-tesla-model-s-fighter-rd-chief-tells-paper

Honda. (2015, November 17). Honda Clarity Fuel Cell sedan makes North American debut at 2015 Los Angeles Auto Show. Retrieved from http://www.hondanews.com/releases/honda-clarity-fuel-cell-sedan-makes-north-american-debut-at-2015-los-angeles-auto-show

Hull, D. (2016, May 4). Musk sleeps near factory floor to spur Tesla manufacturing. Bloomberg. Retrieved from http://www.bloomberg.com/news/articles/2016-05-04/tesla-reaffirms-delivery-forecast-accelerates-assembly-output

Hyundai. (2016, March 23). 2017 Hyundai Ioniq model lineup makes U.S. debut at New York International Auto Show. Retrieved from https://www.hyundaiusa.com/about-hyundai/news/Corporate_2017_HYUNDAI_IONIQ_MODEL_LINEUP_MAKES_US_DEBUT_AT_NEW_YORK_INTERNATIONAL_AUTO_SHOW-20160323.aspx

Kable, G. (2016, August 24). VW's 2019 electric vehicle for Paris motor show reveal. AutoCar. Retrieved from http://www.autocar.co.uk/car-news/new-cars/vw-plans-radical-new-electric-vehicle-2019

Karkafiris, M. (2016a, February 15). All-electric Bentley still a possibility, Bentayga PHEV coming in 2018. CarScoops. Retrieved from http://www.carscoops.com/2016/02/all-electric-bentley-still-possibility.html

Karkafiris, M. (2016b, April 14). LG Chem will build an Electric Car Battery Factory In Poland. CarScoops. Retrieved from http://www.carscoops.com/2016/04/lg-chem-will-build-electric-car-battery.html

King, D. (2015, October 8). GM says li-ion battery cost per kWh already down to $145. AutoBlog. Retrieved from http://www.autoblog.com/2015/10/08/gm-li-ion-battery-cost-per-kwh-already-down-to-145/

Korosec, K. (2015, October 15). Volvo: It's time for electric cars to enter the mainstream. *Fortune.* Retrieved from http://fortune.com/2015/10/15/volvo-electric-cars-lineup/

Kurylko, D. (2016, January 18). BMW will boost i3's range. *Automotive News*. Retrieved from http://www.autonews.com/article/20160118/OEM05/301189994

Lambert, F. (2015, November 19). The electric driving revolution isn't impossible or likely, it's inevitable – Audi President of America. Electrek. Retrieved from http://electrek.co/2015/11/19/the-electric-driving-revolution-isnt-impossible-or-likely-its-inevitable-audi-president-of-america/

Lassa, T. (2015, October 27). Honda Clarity Fuel Cell to spawn plug-in, conventional hybrid variants. *Automobile Magazine*. Retrieved from http://www.automobilemag.com/news/new-honda-fuel-cell-car-spawns-next-gen-plug-in-conventional-hybrids/

Lutsey, N. (2015a, September). *Transition to a global zero-emission vehicle fleet: A collaborative agenda for governments.* International Council on Clean Transportation. Retrieved from http://www.theicct.org/zev-alliance-collaborative-agenda

Lutsey, N. (2015b, December). *Global climate change mitigation potential from a transition to electric vehicles.* International Council on Clean Transportation. Retrieved from http://theicct.org/global-ev-2050-ghg-mitigation-potential

Lutsey, N., Searle, S., Chambliss, S., & Bandivadekar., A. (2015, July). *Assessment of leading electric vehicle promotion activities in United States cities.* International Council on Clean Transportation. Retrieved from http://theicct.org/leading-us-city-electric-vehicle-activities

Mitsubishi. (2011, January 19). Mitsubishi Motors Environment Initiative Program 2015. Retrieved from http://media.mitsubishicars.com/releases/58c6e7c5-bb43-140f-4502-2a014d37cd64

Motoring. (2015, September 5). Next Nissan LEAF to target 400km. Retrieved from http://www.motoring.com.au/next-nissan-leaf-to-target-400km-53658/

Motoring. (2016, January 18). Benz bets big on plug-ins. Retrieved from http://www.motoring.com.au/benz-bets-big-on-plug-ins-100951/

Mr Ghosn bets the company. (2009, October 15). *The Economist.* Retrieved from http://www.economist.com/node/14662050

Musk, E., & Straubel, J. B. (2012, May 9). Model S efficiency and range. Tesla. Retrieved from https://www.tesla.com/blog/model-s-efficiency-and-range

National Research Council. (2015). *Overcoming barriers to the deployment of plug-in electric vehicles.* National Academies Press. Retrieved from http://www.nap.edu/catalog.php?record_id=21725

Nelson, P., Ahmed, S., Gallagher, K., & Dees, D. (2015, June 1). Cost savings for manufacturing lithium batteries in a flexible plant. *Journal of Power Sources* (283): 506-516. Retrieved from http://www.sciencedirect.com/science/article/pii/S0378775315003882

Nissan. (2013). 2013 Nissan LEAF press kit. Nissan. Retrieved from http://nissannews.com/en-US/nissan/usa/presskits/us-2013-nissan-leaf-press-kit

Nissan. (2016). Nissan LEAF®. Nissan. Retrieved from http://www.nissanusa.com/electric-cars/leaf/

Nykvist, B., and Nilsson, M. (2015, April). Rapidly falling costs of battery packs for electric vehicles. *Nature Climate Change* (5): 329-333. Retrieved from http://www.nature.com/nclimate/journal/v5/n4/full/nclimate2564.html

Pontes, J. (2016). EV Sales. Retrieved from http://ev-sales.blogspot.com

Porsche. (2015, December 4). Green light for Mission E. Retrieved from https://newsroom.porsche.com/en/products/porsche-mission-e-concept-study-iaa-e-mobility-12066.html

Randall, T. (2015, August 10). Here's how Elon Musk gets Tesla to 500,000 cars a year by 2020. Bloomberg. Retrieved from http://www.bloomberg.com/news/articles/2015-08-10/here-s-how-elon-musk-takes-tesla-to-500-000-cars-in-five-years

Renault. (2015, December 21). Renault ZOE R240, VAB family car of the year 2016 in the electric vehicles category. Renault. Retrieved from http://media.renault.com/global/en-gb/renault/Media/PressRelease.aspx?mediaid=74519

Saeed, B. (2016, February 16). Here's why Volkswagen will spend $4.5 billion in China this year. *China Business News*. Retrieved from http://www.chinabusinessnews.com/2341-heres-why-volkswagen-ag-will-spend-45-billion-in-china-this-year/

Sedgwick, D. (2015, December 14). LG Chem quietly surges in battery race. *Automotive News.* Retrieved from http://www.autonews.com/article/20151214/OEM06/312149992/lg-chem-quietly-surges-in-battery-race

Shallenberger, K. (2015, September 22). Updated: Tesla Gigafactory will cut battery costs 50%, analyst says. Retrieved from http://www.utilitydive.com/news/updated-tesla-gigafactory-will-cut-battery-costs-50-analyst-says/405970/

Sheehan, S. (2016, May 30). Nissan chases sustainable electric future. AutoCar. Retrieved from http://www.autocar.co.uk/car-news/industry/nissan-chases-sustainable-electric-future

Sinclair, M. (2015, March 5). Mainstream Benz models spearhead PHEVs. Motoring. Retrieved from http://www.motoring.com.au/mainstream-benz-models-spearhead-phevs-49670

U.S. Environmental Protection Agency (U.S. EPA). (2016). Download fuel economy data. Retrieved from United States Department of Energy website: https://www.fueleconomy.gov/feg/download.shtml

Tesla Motors. (2016a). Model 3: Accelerating sustainable transport. Retrieved from https://www.teslamotors.com/model3

Tesla Motors. (2016b). Tesla Gigafactory. Retrieved from https://www.teslamotors.com/gigafactory

Tietge, U., Zacharof, N., Mock, P., Franco, V., German, J., Bandivadekar, A., Ligterink, N., & Lambrecht, U. (2015, September). *From laboratory to road: A 2015 update of official and "real-world" fuel consumption and* CO_2 *values for passenger cars in Europe.* International Council on Clean Transportation. Retrieved from http://www.theicct.org/laboratory-road-2015-update

Toyota. (2016, March 23). Prime mover: Toyota maxes out tech and style in the world's best-selling hybrid to create the 2017 Prius Prime. Retrieved from http://toyotanews.pressroom.toyota.com/releases/nyas+toyota+prius+prime+debut.htm

Volkswagen. (2016, January 5). CES 2016: Electric Volkswagen Budd-e concept brings the microbus into the 21st century. Retrieved from http://media.vw.com/release/1122/

Volkswagen Group. (2016, June 16). New group strategy adopted: Volkswagen Group to become a world-leading provider of sustainable mobility. Retrieved from https://www.volkswagen-media-services.com/en/detailpage/-/detail/New-Group-strategy-adopted-Volkswagen-Group-to-become-a-world-leading-provider-of-sustainable-mobility/view/3681833/7a5bbec13158edd433c6630f5ac445da?p_p_auth=m8U7rmnZ

Wolfram, P., & Lutsey, N. (2016, July). *Electric vehicles: Literature review of technology costs and carbon emissions.* International Council on Clean Transportation. Retrieved from http://www.theicct.org/lit-review-ev-tech-costs-co2-emissions-2016

Yang, Z., Slowik, P., Lutsey, N., & Searle, S. (2016, June). *Principles for effective electric vehicle incentive design.* International Council on Clean Transportation. Retrieved from http://www.theicct.org/principles-for-effective-EV-incentive-design

Yoo-chul, K. (2015, October 27). LG Chem opens mega battery plant in China. *Korea Times.* Retrieved from http://www.koreatimes.co.kr/www/news/tech/2015/10/133_189601.html

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