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POWER PLAY: HOW GOVERNMENTS ARE SPURRING THE ELECTRIC VEHICLE INDUSTRY

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EXECUTIVE SUMMARY

Auto manufacturers have announced more than $150 billion in investments to achieve collective production targets of more than 13 million electric vehicles annually around 2025. This is likely be more than 10% of global light-duty vehicle sales, based on publicly announced plans. To achieve this level of electric vehicle growth, the industry will need to expand battery production by an order of magnitude. This growth amounts to a massive opportunity for technology innovation and economic growth. With such major electric vehicle and battery investments being made over the next several years, it is a critical time to assess where these investments are likely to go based on the market and policy landscape.

Our report includes a detailed assessment of light-duty electric vehicle sales and manufacturing, including the associated battery production and its suppliers. We analyze where electric vehicle models are being assembled and where their battery cells are being produced, and compare that to where the consumer markets are developing. We also investigate underlying policies that have supported the industrial and market developments to date. In so doing, this work looks to assess the status of the major electric vehicle markets through 2017, while also identifying policy opportunities for accelerating the transition to electric.

Some regions have seen greater market growth in electric vehicles, whereas others have seen greater industrial production. Figure ES-1 shows the cumulative electric vehicle sales and production from 2010 through 2017 for major markets. The key part of the value chain for the electric vehicles—the battery cell production source—is also shown. Electric vehicle sales and production are largely concentrated in China, Europe, Japan, and the United States. These four regions account for more than 97% of global electric vehicle sales and 93% of production. Also shown are Japan and South Korea, major battery cell producers that account for about half of the cumulative electric vehicle battery production. The percentage of the cumulative global electric vehicles, which was about 3.2 million through 2017, is shown on right axis.

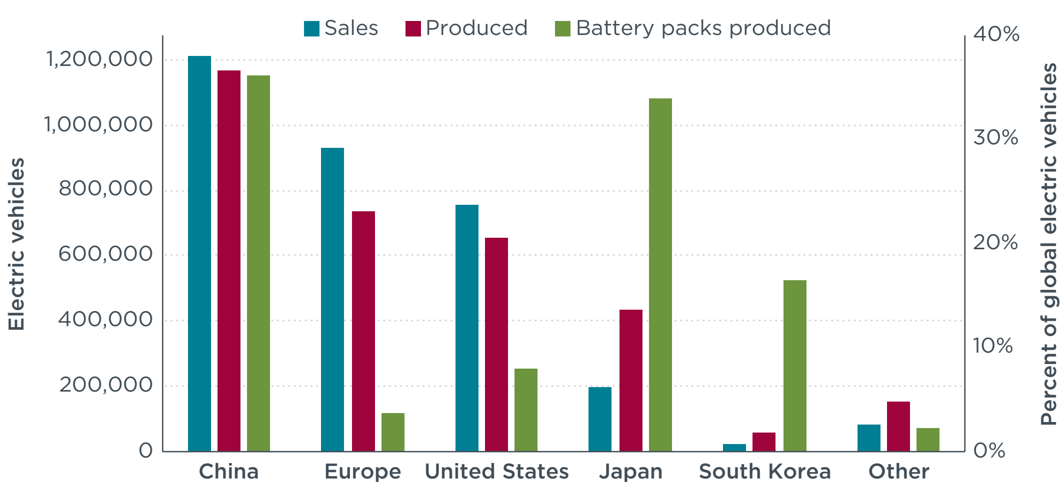


Figure ES-1. Electric vehicle sales, electric vehicle production, and electric vehicle battery production by region through 2017.

Based on this analysis, we summarize the following electric vehicle, battery production, and policy findings.

Electric vehicle production. China, Europe, Japan, South Korea, and the United States account for nearly all global electric vehicle production. China's electric vehicle production was highest with 50% of global production in 2017, followed by Europe with 21%, the United States with 17%, Japan with 8%, and South Korea with 3%. The 20 leading automakers, each with more than 20,000 electric vehicles produced in 2017, represent 94% of electric vehicle production. Of the top 20 electric vehicle manufacturers, nine have headquarters in China, four in Europe, three in the United States, three in Japan, and one in South Korea. Nineteen of the top 20 highest selling models are manufactured in their highest-selling markets, and 11 are manufactured and sold in China.

Electric vehicle battery production. From 2011 to 2015, Japan was by a wide margin the world's largest producer of battery packs for electric vehicles. By 2016, China's battery cell production for electric vehicles overtook that of South Korea and Japan. In 2017, China's battery cell production for light-duty electric vehicles was 11 times that of the United States and 22 times that of Europe. There were six major battery manufacturing companies each with battery cell production for more than 100,000 electric vehicles per year in 2017, showing a clear movement toward economies of scale. Of the 13 top companies that supplied 94% of electric vehicle battery cells in 2017, seven have headquarters in China, three in Japan, and three in South Korea. Based on industry announcements of battery cell production through 2022, China accounts for more than half, compared to 12%–17% each for Europe, South Korea, and the United States.

Electric vehicle promotion policy. Several policies are helping to overcome electric vehicle barriers of limited model offerings, cost, and convenience, especially across China, Europe, and the United States. More than 80% of the world's new automobiles are subject to standards that provide a foundation for industry investments in vehicle technology. A few policies around the world, specifically in California and nine other U.S. states, China, and Québec, directly require increased deployment of electric vehicle models. Consumer incentives play a critical role in reducing electric vehicle costs in the near term as electric vehicle offerings increase and production moves to higher volume. Leading electric vehicle markets are overcoming infrastructure challenges through a combination of power utility and government support actions.

Electric vehicle industrial policy. China has comprehensively promoted domestic and foreign investment in batteries and electric vehicles with its central planning and reinforcing local policy. Setting clear volume targets and providing financial incentives ultimately has vested governments and companies in developing an electric vehicle market and a manufacturing base. Restricting electric vehicle incentives to vehicles with batteries manufactured in China promotes local production and is driving Japan- and South Korea-based companies toward China production. The longstanding condition for foreign companies to partner with China-based companies in joint ventures has led to many major auto manufacturing plants (e.g., with companies like Nissan, BMW, and General Motors), and these are increasingly producing electric vehicles. Policies in the United States and Europe to spur similar electric vehicle and battery investments have been comparatively limited.

I. INTRODUCTION

National and local governments around the world are seeking to accelerate the shift of their vehicle fleets from combustion to electric drive. They are motivated to clean the air for health reasons, to mitigate global catastrophic climate change, and to reduce the cost to their society of importing and combusting petroleum fuels. Electric vehicle markets are developing around the world and the environmental and energy-saving benefits are real and growing.

Many governments are setting clear market signals and are hoping to steer this process toward vehicle electrification. National policy leaders in Germany, India, the Netherlands, Norway, and the United Kingdom all have announced their intention to move toward all electric-drive vehicle sales in the 2025–2040 time frame. State and provincial leaders within these countries and in Canada and the United States have similarly stated their intention to move to zero-emission vehicles over the coming decades. City leaders have become the most progressive of all, indicating their intent to ban diesel, and eventually phase out combustion buses, trucks, and cars within cities.

Yet there is one motivation that may even greatly surpass the clean air, climate change, and oil dependence benefits for some governments. That is the motivation to economically benefit from manufacturing of the future electric car industry. Economies like Japan, Germany, and the United States, among others where there is major automobile manufacturing, have the most to lose if they do not lead in the transition to electric vehicles. China, on the other hand, is now the leading automobile market and has the most to gain from staking out a leadership position in the shift to electric. With its vehicle manufacturing predominantly sold domestically through 2017, the development of electric vehicles could offer China a faster path to expand and export into other vehicle markets.

At this stage in the development of electric vehicles, nearly every automaker has committed to multibillion-dollar investments to develop a spectrum of new electric models. Table 1 summarizes several such announcements, including the associated value of the investment, the number of electric models, and the electric vehicle sales (and shares of new vehicles). In terms of the largest commitment in volume of vehicles, the Renault-Nissan-Mitsubishi commitment of 30% of production would amount to approximately 3 million vehicles per year. The largest announced monetary investment is from the Volkswagen Group, which includes Audi and other Volkswagen brands. Volkswagen committed to 34 billion euros ($40 billion) through 2022 for a launch of 80 electric vehicle models by 2025, and an electric variant on all 300 models by 2030. In turn, the company announced a procurement offer for 50 billion euros ($60 billion) for the battery suppliers for all these electric vehicles.

Table 1. Electric vehicle and battery manufacturing plant investments

Automaker group	Announced investment[a]	Electric models[b]	Annual global electric sales (shares)[c]
Nissan-Renault-Mitsubishi	• $9 billion over 2018–2022 (in China only)	• 12 electric models by 2022	3 million (30%) by 2022
Volkswagen Group	• $40 billion manufacturing plant by 2022 • $60 billion battery procurement	• 80 electric models by 2025 • 300 electric models by 2030	2–3 million (20%– 25%) by 2025
Toyota	• (not available)	• All vehicles hybrid, battery, or fuel cell electric by 2025	2 million (25%) by 2025
Chonqing Changan	• $15 billion by 2025	• 21 electric models by 2025 • 12 plug-in hybrid models by 2025	1.7 million (100%) by 2025
BAIC	• $1.5 billion by 2022 • $1.9 billion (with Daimler)	• (not available)	1.3 million (100%) by 2025
Geely	• (not available)	• All models hybrid or electric by 2019 (Volvo)	1.1 million (90%) by 2020
General Motors	• (not available)	• 20 electric models by 2023	1 million (12%) by 2026
Tesla	• $4–5 billion battery manufacturing	• 3–4 electric models (S, X, 3, Y)	0.5 million (100%) by 2020
Mercedes	• $12 billion manufacturing plant • $1.2 billion battery manufacturing	• 10 electric models by 2025 • 50 electrified models by 2025	0.4–0.6 million (15%–25%) by 2025
BMW	• $2.4–3.6 billion procurement by 2025	• 12 electric models by 2025 • 13 plug-in hybrid models by 2025	0.4–0.6 million (15%–25%) by 2025
Ford	• $11 billion manufacturing plant by 2022	• 16 electric models by 2022 • 24 plug-in hybrid models by 2022	(not available)
Great Wall	• $2–8 billion over 10 years	• (not available)	(not available)
Jaguar	• (not available)	• All models hybrid or electric by 2020	
Inifiniti	• (not available)	• All new models plug-hybrid or electric by 2021	(not available)

Note. Details are from press statements from the companies and media reports at time of announcements.
[a]Assume 1 euro to $1.2 conversion, based on mid-2017 exchange. [b]Models in this column refer to plug-in electric and non-plug-in hybrids. [c]Final column has approximated sales and shares of new vehicles based on announced commitments and 2016 sales volume (excluding non-plug-in hybrids).

Based on the automaker plans in Table 1, collectively more than $150 billion in automaker investment is underway with the annual sales goal of more than 13 million electric vehicles. This likely would exceed 10% of global light-duty vehicle sales in 2025, depending on sales growth. If annual electric vehicle sales increased from 1.2 million, the total in 2017, to 13 million by 2025, this would be a 35% compounded annual growth rate. Many strategic plans are not announced, so the actual investments are likely much greater than shown. Considering the incomplete parts of the table, like investments by General Motors and Toyota, the cumulative investment amount is likely to be much larger. For example, GM indicated it would reach 20 all-electric models by 2023 and turn a profit by 2023, but has not made an announcement about its total investment level. Likewise, BMW and BYD have had among the largest deployment of electric vehicles to date, but estimates of their investments were not forthcoming. Another indication of the scale of future battery investments can be seen in the recent announcement from the European Union Battery Alliance; European Commission Vice President Maroš Šefčovič described the potential battery market value chain as being worth 250 billion euros

($300 billion) annually and the need for Europe to build 10 to 20 factories of at least 1 GWh, at 1 billion euros each (European Commission, 2018).

With all these electric vehicle investments to be made over the next 5–10 years, it is a critical time to assess where these investments will go based on the market and policy landscape. This paper seeks to assess what governments are doing to lead the transition to electric vehicles, which includes encouraging these types of investments in automakers and battery suppliers. Although previous studies have focused on growing the market from the ground up—for example, with incentives and national and local promotion actions—this assessment focuses on top-down efforts by governments to proactively spark the nascent electric vehicle industry. Our assessment includes a detailed assessment of electric vehicle sales and manufacturing, the associated battery production and its suppliers, and the support policies that have supported their development. In so doing, this work looks to assess the positions of the major vehicle markets in steering the transition to electric vehicles, and also to identify policy opportunities to better accelerate the transition.

This analysis of industrial competitiveness is focused on the passenger automobile market, specifically light-duty passenger vehicles, due to its much larger scale than the bus and truck markets. The massive production scale of the auto industry makes it of critical importance in most major economies around the world because of the manufacturing jobs and the revenue involved. In addition, light-duty vehicle use and emissions contribute a large fraction of the transport sector's emissions and energy use in most markets around the world, making it the primary driver of oil use and oil imports. The magnitude of the light-duty automobile market presents an opportunity to drive higher economies of scale, and this in turn could help electrify lower-volume market segments, like medium- and heavy-duty freight vehicles. Although we focus on passenger vehicles, the policies, companies, and technologies in this analysis can apply to heavy-duty commercial vehicles, where there are also growth opportunities.

II. ANALYSIS OF ELECTRIC VEHICLE DEVELOPMENTS

To better understand the electric vehicle industrial landscape, we assess electric vehicle sales, production, battery production, and related factors according to where they are assembled and sold. We compile and assess vehicle sales, registration, production, and model specification data from several sources (ChinaAutoWeb, 2017, EV Sales, 2018; Hybridcars.com, 2018; IHS Markit, 2018; International Organization of Motor Vehicle Manufacturers, 2018; Marklines, 2018). We apply a variety of public data from automakers and government regulatory authorities to assess electric vehicle specifications such as battery capacity and electric range, as well as assembly locations. To analyze all these data for connections and trends, we constructed a database for all makes and models of electric vehicles and where they were assembled and sold from 2010 through 2017. Throughout the report we collectively refer to fully battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) simply as electric vehicles.

ELECTRIC VEHICLE SALES AND PRODUCTION

Figure 1 shows the electric vehicle sales and production from 2010 through 2017 for major markets. As shown, electric vehicle sales (vertical axis) and production (horizontal axis) are largely concentrated in China, Europe, Japan, and the United States. These four regions account for about 97% of sales and 93% of the manufacturing of electric vehicles. Although South Korea's electric vehicle sales and production are low, it plays a major role in battery production, which will be discussed below. The China market is the largest with about 1.2 million sales and production of electric vehicles through 2017. Beyond these four regions, there are small amounts of electric vehicle sales in several other markets. The percentage of the global electric vehicle production of about 3.2 million electric vehicles through 2017 is labeled and shown by the size of circles in the figure.

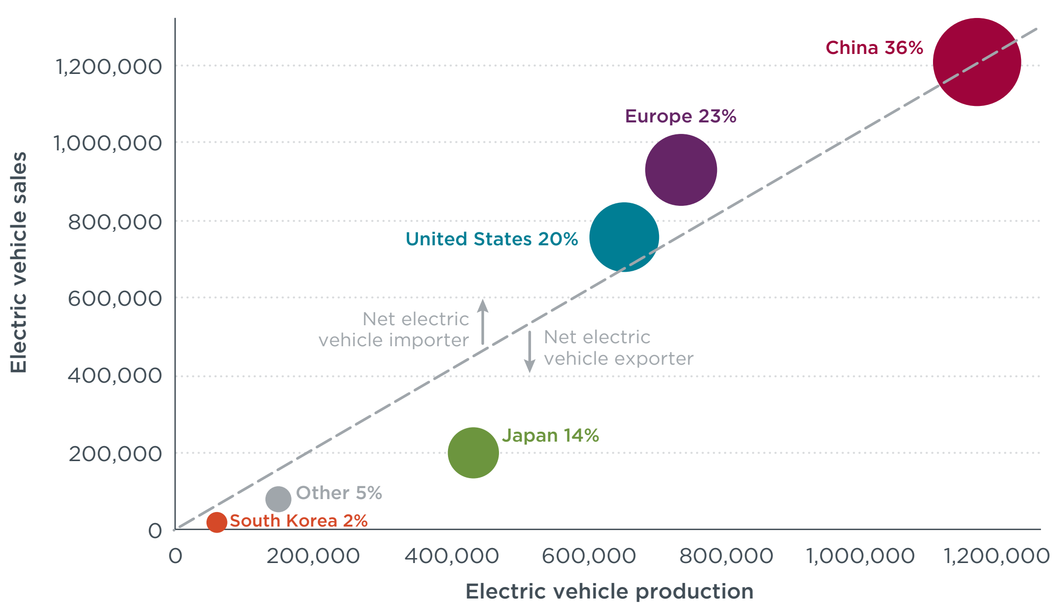


Figure 1. Cumulative electric vehicles sales and production from 2010 through 2017, in major regions, with circle size proportional to the percentage of global electric vehicles produced.

The diagonal line in Figure 1 represents equal sales and production. Therefore, markets above the line are net importers of electric vehicles, where there have been more market sales than were produced by industry in that market area. For example, more than 930,000 electric vehicles have been sold in Europe compared to about 740,000 produced there. Conversely, markets below the line have had greater electric vehicle production than sales and have therefore been net exporters to the rest of the world. For example, more than 430,000 electric vehicles have been produced in Japan compared to 200,000 sold there. Although the trends show the three main markets of China, Europe, and the United States each manufacturing 20%–36% of 2010–2017 electric vehicles, recent trends have shifted more toward China. China accounted for about 50% of electric vehicle production in 2017. Details related to the more recent underlying trends are assessed below.

ELECTRIC VEHICLE BATTERY AND SUPPLIER DEVELOPMENT

Listing the vehicle manufacturing companies and the associated battery suppliers gives a more detailed picture of the emerging electric vehicle industry. Figure 2 depicts the sales growth of electric vehicles and the associated electric vehicle battery packs, by company. As shown, the annual sales has substantially increased from hundreds in 2010 to about 1.2 million by 2017. The cumulative total of all electric vehicles through 2017 is approximately 3.2 million.

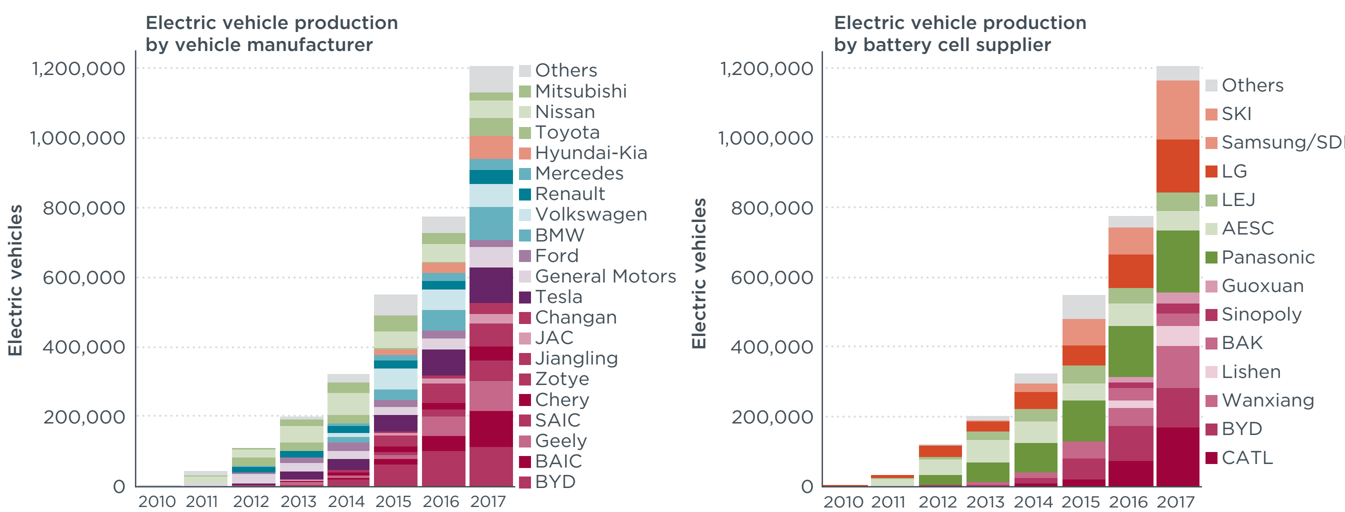


Figure 2. Electric vehicle and battery pack cell production by automobile manufacturer and battery pack supplier for 2010–2017.

As shown in Figure 2, the number of electric vehicle manufacturers and the scale of their production have increased steadily. The companies are sorted according to region (e.g., the nine auto companies in China are together in the left part of the figure), with the colors approximately linked to company regions: shades of red for China, blue for Europe, green for Japan, orange for South Korea, and purple for the United States. Vehicle manufacturer data show that 20 companies are each now producing more than 20,000 electric vehicles annually. Ten companies—BAIC, BMW, BYD, Geely, GM, Hyundai-Kia, SAIC, Tesla, Toyota, Volkswagen—each had more than 50,000 in annual sales in 2017, up from five such companies in 2016. The 20 companies shown represent 94% of electric vehicle production in 2017. In terms of regional representation by these vehicle manufacturers, nine have headquarters in China, four in Europe, three in the United States, three in Japan, and one in South Korea. We note that precise categorization of the companies and regions becomes difficult due to joint ventures, alliances, and joint efforts between suppliers and automakers on electric vehicle components. For example, we show Nissan, Renault, and Mitsubishi as separate in the figure, although they have an alliance on their technology developments. In the "others" category, automobile companies that are not named due to fewer electric vehicle sales in 2017 include Citröen, Fiat-Chrysler, Honda, Mazda, Peugeot, and Subaru.

The number of battery suppliers for these electric vehicles and these suppliers' annual production have both increased since 2010, as shown in the right side of Figure 2. With fewer companies than in the electric vehicle portion of the figure, it is evident that suppliers are serving multiple vehicle manufacturers and achieving higher production scale more quickly. The suppliers are grouped by region and listed in order of 2017 battery pack production, from the bottom up. We estimate that there are six battery manufacturing companies—Panasonic, Contemporary Amperex Technology Co. Limited (CATL), LG, Samsung SDI, BYD, and Wanxiang—with battery production for more than 100,000 electric vehicles per year in 2017. The first four of these each produce battery cells for more than 150,000 electric vehicles per year. These top 13 electric vehicle battery cell producers represent 94% of electric vehicle battery packs produced in 2017. Of the companies shown, seven have headquarters in China, three in Japan, and three in South Korea. However, we emphasize again that these companies are largely global with joint ventures and their manufacturing supply chains span the regions.

To provide more specific examples of the electric vehicle sales and assembly location, Table 2 summarizes the top 20 electric vehicle models according to estimated global sales in 2017. The table summarizes the major sales markets, vehicle assembly locations, battery cell production locations, 2017 sales, and cumulative 2010–2017 sales. The 20 models shown each had global sales of at least 17,000, and the top 10 had more than 28,000 sales in 2017. We note that several of the battery packs have *cell* production as indicated but battery *pack* assembly into automotive packs occurs in other regions. For example, the Chevrolet Volt battery pack is assembled in Michigan, whereas the cells are manufactured by LG in South Korea. Among these top 20, nine models were BEVs, six were PHEVs, and five were available as either BEV or PHEV.

Table 2. Electric vehicle models, assembly locations, and estimated sales

Vehicle model	Type	Major sales market	Vehicle production	Battery cell production	Sales 2017	Cumulative sales 2010-2017
BAIC EC-series	BEV	China	China	China	81,000	90,000
Tesla Model S	BEV	Canada, China, Europe, US	US	Japan	55,000	210,000
Toyota Prius	PHEV	Japan, US	Japan	Japan	51,000	120,000
Nissan Leaf	BEV	Europe, Japan, US	Japan, Europe, US	Japan	47,000	300,000
Tesla Model X	BEV	Canada, China, Europe, US	US	Japan	47,000	70,000
Zhidou D2	BEV	China	China	China	42,000	60,000
BYD Song	BEV, PHEV	China	China	China	35,000	30,000
Renault Zoe	BEV	Europe	Europe	South Korea	32,000	90,000
BMW i3	BEV, PHEV	Europe, US	Europe	South Korea	31,000	100,000
Roewe eRX5	BEV	China	China	China	30,000	30,000
Chevrolet Bolt	BEV	Canada, US	US	South Korea	28,000	30,000
Chery eQ	PHEV	China	China	China	27,000	50,000
Chevrolet Volt	PHEV	Canada, US	US	South Korea	26,000	150,000
BYD e5	BEV	China	China	China	26,000	70,000
JAC iEV	PHEV	China	China	China	26,000	30,000
BYD Qin	BEV, PHEV	China	China	China	26,000	100,000
Mitsubishi Outlander	PHEV	Europe, Japan	Japan	Japan	26,000	140,000
Geely Emgrand	PHEV	China	China	China	25,000	40,000
BMW 330e	BEV, PHEV	Europe, US	Europe	South Korea	20,000	30,000
Hyundai Ioniq	BEV, PHEV	Europe, South Korea	South Korea	South Korea	17,000	20,000

Note. Based on EV sales, 2018; Hybridcars, 2018; IHS Markit, 2018; Marklines, 2018; and media reports. Major sales markets had at least 1,000 sales in 2017. All sales and cumulative sales estimates are rounded to the nearest thousand.

As shown in Table 2, four of the top five models are sold in multiple markets. These higher production levels help enable greater economies of scale. Another general takeaway from the data is that 19 of the 20 models of the highest-selling electric vehicle models are manufactured in their highest-selling markets. The only exception is the Mitsubishi Outlander, which is made in Japan and sold primarily in Europe. As for the battery suppliers of the 20 top-selling vehicle models, the battery cell production is in China, Japan, and South Korea in all 20 cases. One unique element among these 20 models is that the Nissan Leaf, the highest-selling 2010–2017 model with about 300,000 cumulative sales, was assembled in three major plants on three continents.

Matching how the China market now amounts to approximately 36% of the cumulative global electric vehicle sales to date, China shows up the most in Table 2. Of the 20 top-selling global electric vehicle models, 11 were sold in China. The models that are built in China—nine of the top 20—are sold predominantly in China. Conversely, nearly all the high-selling electric vehicles that are made outside of China are largely unavailable in China. Tesla models are the exception. In terms of cumulative sales, seven of the models have reached or surpassed 100,000 total sales through 2017.

ELECTRIC VEHICLE COST COMPONENTS

To better understand the technology components of electric vehicles and their importance in the electric vehicle cost proposition, we drew from several recent studies, including a detailed engineering teardown cost analysis. Teardown studies are used to assess the costs to manufacture vehicles, piece-by-piece, including materials, labor, and assembly cost. These are typically used in the auto industry to better understand competing automaker or supplier technologies, their materials, the assembly techniques, and associated costs. We use the cost breakdown to better understand the importance of various electric vehicle technology areas and related manufacturing opportunities for companies.

Figure 3 summarizes the breakdown of representative electric vehicles, according the content of the final assembled vehicle by the original equipment manufacturer (OEM). The figure shows a detailed breakdown of parts on the first long-range (i.e., greater than 200 miles) and low-cost (i.e., less than $40,000) electric vehicle, the Chevrolet Bolt, as reported by UBS (2017). The 2017 gasoline vehicle estimates also come from the UBS report, which uses primarily the gasoline Volkswagen Golf as the comparable gasoline vehicle. To explore the prospect of lower-cost batteries, we include both UBS' estimated 2025 cost, based on $130 per kilowatt-hour (kWh) battery pack. We also include a further breakthrough to a $100 per kWh battery pack (Kittner, Lill, & Kammen, 2017).

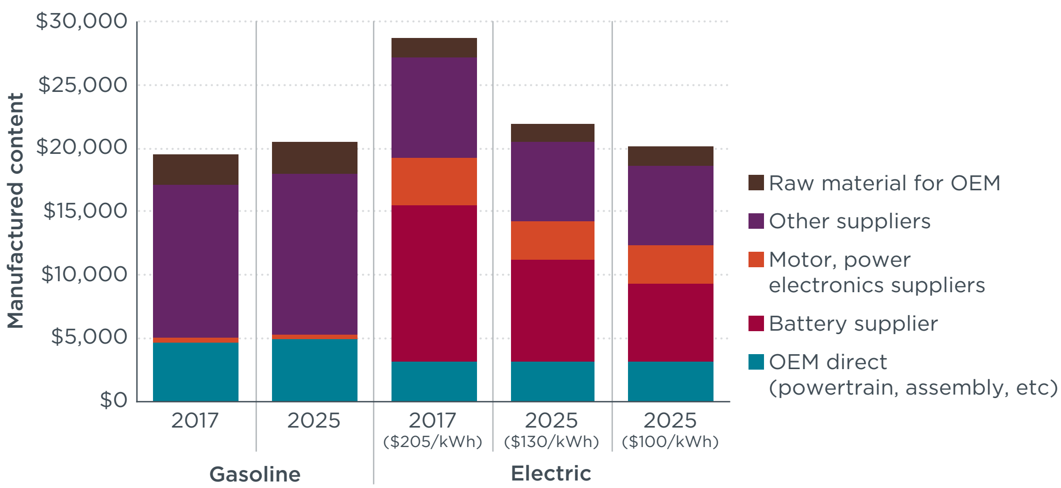


Figure 3. Breakdown of manufactured cost of gasoline and electric vehicles.

As shown in the figure, electric vehicle cost approaches conventional vehicles around 2025 as battery pack costs fall to $100 to $130 per kWh. This comparison excludes indirect costs, such as research and development, which are higher in the near term for electric vehicles, and also excludes incentives, taxation differences, and consumer fuel savings that make electric vehicles less costly to own than gasoline vehicles. As part of this comparison, we incorporate a cost increase for conventional vehicles to meet efficiency standards, which is estimated to increase costs by 2%–3% or about $800–900 from 2017 to 2025 (Lutsey, Meszler, Isenstadt, German, & Miller, 2017; Meszler, German, Mock, & Bandivadekar, 2016).

Figure 3 shows the breakdown of vehicle content, based on whether it is from the OEM or various suppliers across the several broad categories. The major categories for the conventional gasoline vehicle include OEM direct costs, supplier costs, and raw material.

The electric vehicle cost structure includes a battery supplier now taking the largest percentage, new electric motor and power electronics components, and shifts in the other costs elements. The OEM's direct powertrain and assembled content is about 20%–24% in the conventional gasoline vehicle case, but this drops to 10%–14% in the electric vehicle case. The largest impact on the electric vehicle cost is replacing the traditional engine-based powertrain with the battery pack—representing more than 40% of all vehicle content in 2017, and 31%–35% in 2025—and to motor and other power electronics, which are 13%–15% of the content. We note that within the battery pack cost, about 50%-70% is likely to be in the battery cell production, with the remaining 30%-50% in the pack-level components and assembly (Schade and Mader, 2016; Anderman, 2017). Remaining suppliers' content, excluding the battery, motor, and power electronics, would drop approximately in half from 62% in the gasoline vehicle case to 28%–31% in the electric vehicle.

This context on manufactured content is presented to help illustrate the opportunity for electric vehicle, battery pack, and other component suppliers to manufacture major systems of the vehicle. The analysis shows how the critical cost reduction area for electric vehicles is the battery pack, because of its high current cost and high potential to greatly decrease. This makes improving the battery pack the primary way for new companies, automobile manufacturers, and battery suppliers to innovate and compete by achieving higher production scale. As the figure indicates, this also challenges OEMs and suppliers to become part of the battery pack production business to avoid losing large fractions of the value of the vehicle to new battery supply companies. As a result, we further assess the company developments related to expanding the production of battery packs for electric vehicles.

ELECTRIC VEHICLE BATTERY CAPACITY

To supplement the preceding analysis of the electric vehicle market and to provide context for the assessment that follows, we assess the trends with electric vehicle battery capacity and the location of electric vehicle battery production by region. To do so, we collect global data and analyze the electric vehicle model-specific sales and battery pack capacity. More electric vehicle models across PHEVs and BEVs across a spectrum of battery capacities continue to enter the fleet. Larger battery packs from 60–100 kWh are used on the Tesla Model S and Model X, the BYD e6, and the Chevrolet Bolt BEVs. Smaller battery packs of 5–10 kWh are used on shorter-range PHEVs, for example the BMW 330e, Ford's Fusion Energi and C-Max Energi, and the Volkswagen Golf GTE. There are many shorter range BEVs and longer-range PHEVs that fill out the spectrum, enabling different options for electric range and cost.

Figure 4 shows the sales-weighted battery capacity of electric vehicles in the three major electric vehicle markets of China, Europe, and the United States. As shown, the BEV battery capacity has increased most dramatically in the United States, from 25 kWh in 2014 to 65 kWh in 2017. This is primarily due to the increase in Tesla and Chevrolet Bolt models with much longer electric ranges. The increase in BEV range for the China and Europe markets was more incremental, going from 23 to 39 kWh in Europe, and from 22 to 27 kWh in China, from 2014 to 2017. The PHEV battery capacity increase from 2014 to 2017 was from 13 to 15 kWh in China, and from 11 to 12 kWh in the United States and in Europe. One major difference in the three markets in 2017 is that whereas China's electric vehicle market is 81% BEV, the U.S. and European markets have approximately even splits between BEVs and PHEVs—the U.S. market was 51% BEV and Europe's was 45% BEV.

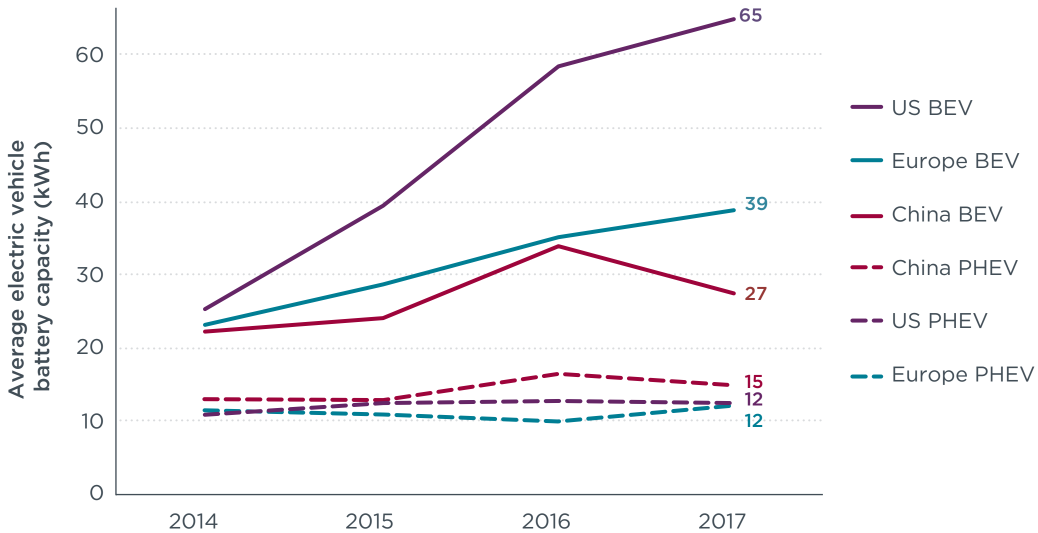


Figure 4. Average battery capacity of electric vehicles sold in China, Europe, and the United States for 2014–2017.

Combining the electric vehicle battery capacity with the country where the battery cells were produced allows us to analyze the trend in sourcing of electric vehicle battery production. Figure 5 summarizes the total electric vehicle battery production through 2017 in gigawatt-hour (GWh). As shown, Japan had been the battery cell-producing leader for electric vehicles through 2015. China's battery cell production for electric vehicles increased significantly to surpass South Korea's in 2015, and then Japan's in 2016, to become the world leader. As shown in the figure, China's battery cell production in 2017 was 11 times that of the United States and 22 times that of Europe. The China battery growth is related to China being the largest electric vehicle sales market, with nearly all of its sales being from domestically manufactured vehicles, and also due to the high number of BEVs with larger battery packs than PHEVs. Although not depicted in the figure, 84% of the cumulative electric vehicle battery pack capacity is in BEVs and 16% is in PHEVs.

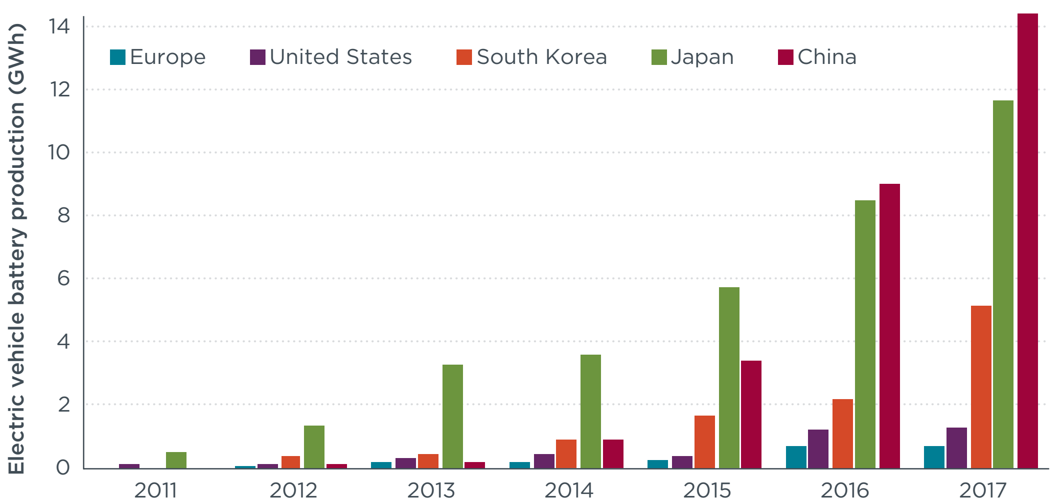


Figure 5. Electric vehicle battery cell production in five regions for 2010–2017.

The leading China-headquartered battery suppliers, such as BYD and CATL, are key in China's growth as shown in Figure 5. The trend could increase because some of the manufacturing companies based in Japan and South Korea are now developing large-scale production in China, a topic to which we will return. We emphasize that the scope of this assessment is centered on light-duty passenger vehicles. The dominance of China's battery production would be more pronounced if electric bus battery production were included, because most electric buses and their batteries are manufactured in China.

Figure 6 shows the electric vehicle production and the electric vehicle battery production in 2017 for major markets. The figure shows electric vehicle production on the vertical axis and electric vehicle battery pack production on the horizontal axis. The percentage of the global 2017 electric vehicle assembly, which produced about 1.2 million vehicles overall, is labeled and shown by the size of circles in the figure. China, Europe, Japan, South Korea, and the United States represent nearly all of the global electric vehicle production in 2017. The Electric vehicle assembly in China in 2017 is the largest with about 50% of global electric vehicle production in 2017, followed by Europe with 21%, the United States with 17%, Japan with 8%, and South Korea with 3%.

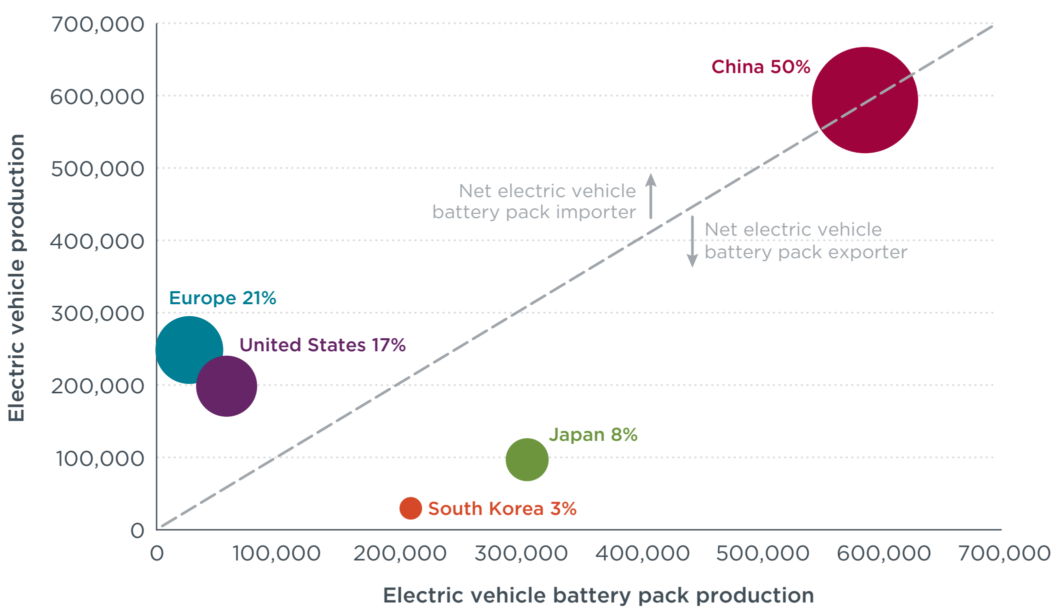


Figure 6. Electric vehicle production and battery production for five major electric vehicle manufacturing regions in 2017, with circle sizes proportional to the percentage of global electric vehicle production.

The diagonal line superimposed on Figure 6 helps to illustrate which markets were importing batteries for their electric vehicle production in 2017. Those markets above the line have greater electric vehicle production than battery production in their region, thus are net battery pack importers, whereas those below are net exporters. The major dynamic shown in the figure is that Japan and South Korea are exporting battery packs to Europe and the United States for electric vehicle production in those two regions. Despite there being nearly 50,000 electric vehicles sales in Japan, approximately twice that many electric vehicles and about six times as many electric vehicle batteries were produced there. Although South Korea had just about 14,000 electric vehicle sales in 2017, more than twice as many electric vehicles and 15 times as many electric vehicle batteries were produced there. On the other hand, the United States produced about 29% as many electric vehicle batteries as the electric vehicles it assembled. Europe produced just 11% as many electric vehicle batteries as the electric vehicles it assembled. As we do throughout this report, we refer to the electric vehicle battery origin by the battery cell production, rather than where those cells are assembled into battery packs.

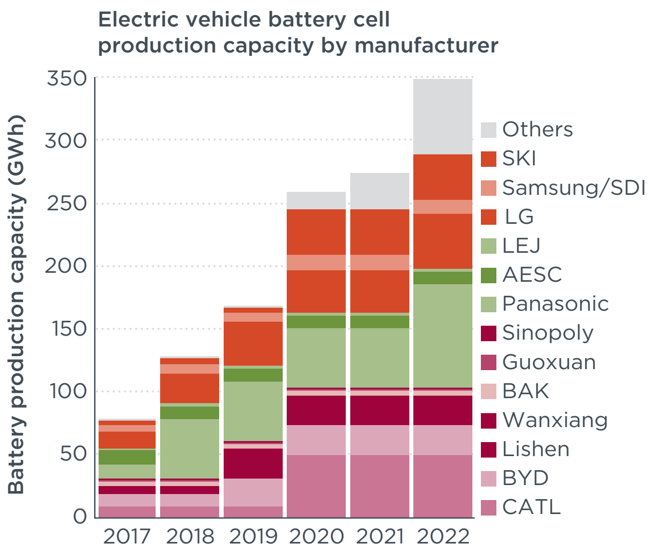
ANNOUNCED ELECTRIC VEHICLE BATTERY CAPACITY EXPANSIONS

There are many in-development and announced plans to increase battery production for electric vehicles through the early 2020s. Table 3 summarizes the announcements of new plants for increased electric vehicle battery production, as well as the planned expansions of existing plants by major battery suppliers, in GWh of new battery packs. The specific years listed in the table are uncertain estimates based on available press releases and media articles. As shown, at least seven new plants have been announced in Europe, and at least four new plants in China, in the approximate 2020 time frame. New battery plants would amount to well over 150 GWh by 2020, and potentially well over 300 GWh before 2025. Another eight plants have planned expansions in battery production capacity by 2020. In total, the battery plant expansions of existing facilities amount to more than 50 GWh in increased annual production.

Table 3. Announced and reported new electric vehicle battery production plants and estimated capacity expansions for 2018–2025 assumed in this analysis

Plant type	Company	Location	Battery production capacity (GWh)	Potential completion timing	Source
New	**LG**	Wroclaw, Poland	4	2018	Goettig, 2017
	SDI	Göd, Hungary	2.5	2018	SDI News, 2017
	Tesla	Nevada, United States	35	2018	Tesla, 2017
	BYD	China	13	2020	Economist, 2017
	Lishen (multiple)	China	17	2020	Sanderson, 2017
	CATL (multiple)	China	37-42	2020	Sanderson, 2017
	SKI	Hungary	7.5	2020	Manthey, 2017
	TerraE	Europe	5	2020	Mussig, 2017
	GSR	Sweden	30	2020–2025	Valle, 2018
	Northvolt	Sweden	32	2020–2025	Pollard, 2017
	Tesla	Europe	35	2020–2025	Lambert, 2016b
	Tesla	Shanghai, China	35	2020–2025	Lambert, 2017a,b,c
	Tesla	To be determined	35	2020–2025	Lambert, 2017d
Expansion	**LG**	Nanjing, China	6	2018	Sanderson, 2017
	LG	Michigan, United States	2	2018	Sanderson, 2017
	LG	Ochang, South Korea	10	2019	Sanderson, 2017
	SKI	Seosan, South Korea	25	2020	Woo-hyun, 2017
	BPP	Liyang, China	7	2020	Sanderson, 2017
	SDI	Xian, China	2	2020	Sanderson, 2017
	SDI	Ulsan, South Korea	2	2020	Sanderson, 2017
	CALB	Luoyang, China	2	2020	Sanderson, 2017
	LG	Wroclaw, Poland	9	2020–2025	Eckl-Dorna & Sorge, 2017
	TerraE	Europe	29	2028	Mussig, 2017

Based on these reports, we summarize the total approximate future battery production for electric vehicles by battery supplier and by cell manufacturing location in Figure 7. As shown, production capacity in 2022, based on announcements to date, would increase by about a factor of four from the 2017 level. This amounts to a 35% compounded annual increase from 2017 through 2022. The data represent uncertain estimates for when the battery production capacity could come on line based on the announcements. The data include the capacity to serve electric cars, electric trucks and buses, and also battery replacement packs, which could eventually be more substantial for electric buses. This caveat is emphasized, as the above analysis of the status of the market through 2017 is based on specific makes and models of light-duty vehicles sold. We acknowledge that some battery production capacity will not meet the announced production schedules, whereas others that have not yet been announced will come on line.



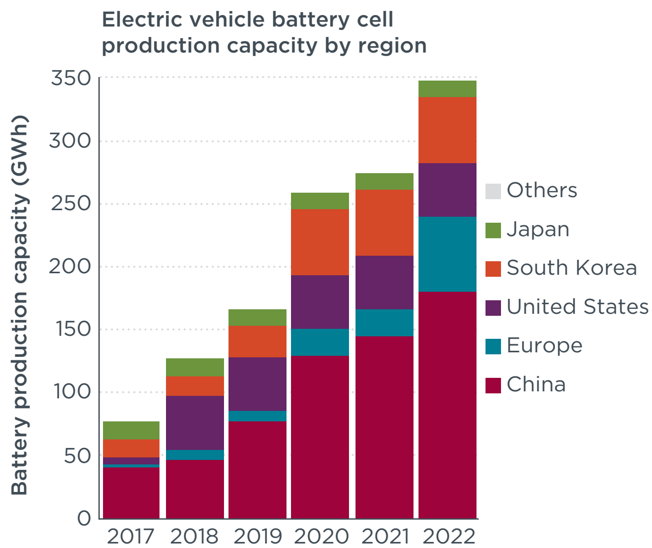


Figure 7. Announced electric vehicle battery pack production capacity for 2017–2022, by company and region.

Several trends in the near-term expansion of global electric vehicle battery production capacity are evident in Figure 7. The biggest gains in announced battery production capacity are in China and align with the central government's guidance and action plan to promote the electric vehicle battery industry toward a goal of 100 GWh in capacity by 2020 (Ministry of Industry and Information Technology [MIIT], 2017d). Production capacity in China remains roughly half of global electric vehicle battery capacity through the 2017–2022 time frame. From just the two biggest China-based battery manufacturers—BYD and CATL—capacity in China is expected to increase by 50–55 GWh by 2020. Additionally, Lishen plans to expand capacity by 17 GWh, and Tesla is seeking to enter the Chinese market with a major factory in China before 2025. Along with planned expansions by LG, SDI, and Boston Power for their respective Chinese plants, additional battery production capacity in China is expected to exceed 100 GWh from 2017 to 2022, increasing the world-leading total capacity to about 180 GWh. South Korean expansions would increase capacity there by a factor of 3, from 15 to over 50 GWh, bringing its fraction of world battery capacity to 15%. Based on these announcements, electric vehicle battery capacity in Japan would decrease to about 4% of global production, as we found no announced new plants there and Japan-based manufacturers are expanding production in China.

By 2022, as shown above, European battery production would increase to about 17% of global capacity, compared to about 12% in the United States, if the more near-term announcements were borne out. About 14 GWh would come from two battery plants for SDI and SKI to be located in Hungary and one for LG Chem in Poland. The TerraE announcements indicate 5 GWh could be added by 2020, before much greater capacity additions by around 2028. A new plan by GSR Capital, which also bought Nissan's AESC battery interest, would produce electric vehicle batteries at up to 30 GWh in Sweden at a NEVS facility. Although similarly not confirmed by clear construction plans, Tesla has indicated it could build another 35 GWh "gigafactory" in Europe, and Northvolt also has announced plans for a similarly large plant in Sweden. As shown, we assume one of these large European plants will be built by 2022, bringing the announced battery production capacity for Europe to about 60 GWh by 2022. If one more of the larger European plants were built by 2022, that would bring the estimated added battery production capacity in Europe to nearly 100 GWh. Based on an average of 40–50 kWh per battery pack, 100 GWh of annual capacity in Europe would have the ability to supply batteries for 2 to 2.5 million electric vehicles annually. In addition, Accumotive, a subsidiary of Daimler, began construction of a large battery plant in Germany in 2017, with production slated to start in 2018, but without an announcement about the battery production capacity. For the United States, there seem to be no other confirmed major electric vehicle battery plants to be built other than the Tesla Panasonic 35 GWh plant in Nevada. LG plans to expand capacity at its Michigan plant, but this is expected to only add 2 GWh of annual capacity.

Although an estimated 2022 capacity of about 350 GWh is more than four times the 2017 production capacity of about 77 GWh, several new studies make it clear that much more battery capacity will be needed to meet electric vehicle expectations. UBS indicates that an equivalent of 14 gigafactories, with a total capacity of 712 GWh in annual capacity, will be needed by 2025 in a world where 14 million electric vehicles are expected to be sold annually (UBS, 2017). Volkswagen has observed that, in 2025, if all major vehicle manufacturers were to target 25% of their sales volumes from electric vehicles, 1,400 GWh of annual battery capacity would be needed to avoid a shortage of lithium-ion battery cells (Hetzner, 2017). This broader context is noted to help highlight that, even if the exact battery supplier production announcements previously noted are uncertain, the trend toward similar global battery production growth is still relatively clear.

III. POLICIES IN LEADING ELECTRIC VEHICLE MARKETS

Going beyond the previously discussed developments in electric vehicle production and sales across global markets, this section looks at the set of policy actions in place to spur that market development. We provide short summaries of consumer incentives, electric vehicle charging infrastructure, and consumer awareness actions in general use that work on the "demand side." After that introduction, the section focuses primarily on identifying and summarizing "supply-side" actions to spur the manufacturing industry to meet the increasing future electric vehicle demand and accelerate the transition to higher electric vehicle production scale. Examples and descriptions of the more recent new and announced manufacturing facility expansions are provided.

MARKET DEVELOPMENT POLICIES

The development of electric vehicle markets includes overcoming several market barriers. These market barriers are typically summed up as limited availability of electric models, higher cost, inconvenience related to charging options, and consumer awareness and understanding about electric vehicles. The major electric vehicle markets have partially overcome these barriers to accelerate uptake as more electric vehicle models enter the market, continue to improve technologically, and experience cost reductions.

Regulatory policy

Regulatory policy sends a clear signal for automakers to make long-term investments and pushes the deployment of their lower-emission models into the market. As of 2016, more than 80% of the world's automobile manufacturing is subject to efficiency or carbon dioxide (CO_2) standards that require vehicles to get more efficient over time (International Council on Clean Transportation, 2016). The standards typically require that the average new vehicle fleet achieves 3% lower CO_2 emissions per kilometer each new model year. The regulated markets that cover the most annual vehicle sales include China, the United States, the European Union, Japan, India, South Korea, Canada, and Mexico. Most standards pertain to model year 2020 or 2021, except for the U.S. standards, which go through 2025. Beyond simply developing more stringent efficiency or CO_2 regulations, particular incentive provisions are used to further spur the use of electric vehicles. The regulations typically provide special provisions for electric vehicles, including counting them as 0 grams CO_2 per kilometer and counting them multiple times (with super credits or multipliers), to promote and reward companies with greater electrification plans.

There are also a few policies around the world that directly require the deployment of electric vehicles. The California Zero-Emission Vehicle regulation has been adopted by California and nine other states, together representing 29% of U.S. light-duty vehicle sales. Complying with the ZEV regulation will mean the California market would have to see an increase to about 8% by 2025 (California Air Resources Board [CARB], 2017). As of 201, California's new vehicle sales were 3.6% electric vehicles, about four times that of the U.S. average (Lutsey, 2017). In 2017, California's electric vehicle sales increased to about 4.8%, and there were 30 California cities that had electric vehicle sales shares above 10% in 2017 (Lutsey, 2018). In addition, the Province of Québec has adopted a ZEV regulation that will require a similar increase in electric vehicle shares through 2025 (Québec, 2018). The other major program that will directly require increased electric vehicle deployment is China's New Energy Vehicle quota system, which will require that electric vehicle share of new vehicle sales increases from 1% in 2016 to approximately 4%, and possibly much higher, by 2020 (Cui, 2018). Recently the central government authorities in China released its strategy document for the auto industry for 2025, which includes the target of 20% of new vehicles to be plug-in electric (MIIT, 2017a). The European Commission and European Union member states have been considering electric vehicle quotas within their post-2021 regulations (Bellona, 2017). In the latest European Commission proposal for 2025 and 2030 standards, electric vehicle targets were included to provide an incentive for manufacturers, but without binding quotas (Dornoff, Miller, Mock, & Tietge, 2018).

To broadly reach prospective electric vehicle consumers, having sufficient electric vehicle models across vehicle sizes, types, and brands is a prerequisite. Efficiency or CO_2 regulations are necessary for industry investment and deployment. When the regulations are sufficiently stringent—for example, set on a long-term path toward near-zero emissions by 2040–2050—or include direct ZEV requirements as in California and nine other U.S. states, China, and Québec, electric vehicle models will enter markets with inventory that is comparable to conventional vehicles. With more inventory comes more marketing, dealer training, and industry effort.

Consumer incentives

Consumer incentives play a critical role in reducing electric vehicle costs in the near term while they remain higher than conventional vehicles . Essentially every major electric vehicle market across Asia, Europe, and North America with more than a 1% electric share of new vehicles has had substantial consumer financial incentives. Typically, these incentives have been $5,000 to $10,000 per vehicle, meaning they substantially reduce the cost difference between electric and comparable nonelectric models (Yang et al., 2016). The markets with the highest global electric vehicle shares have had even larger incentives. For example, major markets in China, the Netherlands, and Norway with over 10% electric share each have had national incentives valued at more than $10,000 per vehicle, and the China markets had additional local incentives (Hall, Moultak, & Lutsey, 2017).

Figure 3 illustrates the need for governments to phase down incentives between 2017 and 2025 to sustain continued electric vehicle growth. Slowik and Lutsey (2016) indicate how incentives ideally are tapered down to match the drop in battery costs through the 2020–2025 time frame, and also how incentives are needed somewhat longer in markets like the United States, where fuel costs are lower. China has announced it will phase down its incentives between 2017 and 2020. The use of federal U.S. tax credits is likely to phase down between 2018 and 2025 as each automaker reaches its maximum of 200,000 eligible electric vehicles. Incentives in Norway, the United Kingdom, France, and the Netherlands, are each reconsidered on an approximately annual basis.

The incremental cost of electric vehicles compared to conventional vehicles is driven primarily by the battery pack cost, which itself is driven by battery technology and production scale. As discussed below, this is a key reason why several governments are trying to simultaneously use manufacturing-level incentives to push for higher-volume battery production faster.

Charging infrastructure

Although the ability to charge electric vehicles at home provides a direct convenience benefit to most drivers, electric vehicles still have barriers related to charging infrastructure. The two key barriers are in the charging availability and time required to charge. These barriers are overcome through the creation of a charging infrastructure ecosystem that enables convenient, affordable charging at many locations within consumers' weekly travel patterns, with sufficiently fast charging.

A full ecosystem of charging options is necessary to enable substantial electric vehicle market expansion, as it helps overcome barriers of consumer confidence, driver range confidence, and awareness. Home charging, when private and garage parking is available, covers most charging needs for most customers. However, as illustrated in several studies, public charging and workplace charging infrastructure are both linked to higher electric vehicle uptake in the United States (Slowik & Lutsey, 2017). The statistical link between public charging and EV uptake is confirmed by global data; leading global markets in Norway, with an electric vehicle share of more than 30%, and Netherlands, with about a 5% electric vehicle share, have 10 times the U.S. average public charging per capita (Hall & Lutsey, 2017b).

The leading electric vehicle markets are overcoming infrastructure challenges through a combination of electric power utility, local and national government, and public-private partnership actions. Government and utility support will be important in the early market as viable business models for public charging infrastructure emerge for local and highway corridor networks. Utilities anticipate broad benefits for all their customers, including reduced rates and managing grid loads, from utilizing ratepayer revenue to fund public charging infrastructure (Ryan & Lavin, 2015).

INDUSTRIAL POLICY FOR BATTERY PRODUCTION

To further spur the electric vehicle industry, industrial policies often are used in combination with market development policies. As previously introduced, the critical and dominant individual cost component for electric vehicles is the battery pack. Automakers and battery suppliers are increasingly planning for a much greater scale of lithium-ion battery pack production to reduce the time it takes to reach profitable electric vehicle production. To further accelerate this transition, many governments have promoted electric vehicle battery production with a series of incentives, requirements, and taxation exemption. The following summarizes developments in China, Europe, and the United States.

Battery production developments in China

As previously noted, China had the highest national electric vehicle battery production in the world in 2017, increasing its margin over Japan and South Korea production since 2016. Based on recent announcements, China appears to be on a continued growth trajectory. China has promoted domestic battery production facilities with a variety of different policies and tax incentives.

Battery suppliers have been the beneficiaries of government subsidies. The central China government is now restricting these subsidies to only larger battery production facilities, essentially encouraging the leading facilities to grow more rapidly. At the end of 2016, the Chinese government released its revised Vehicle Power Battery Industry Standards, which specify that, in order to qualify for subsidies, lithium-ion battery manufacturers would need to have at least 8 GWh of production capacity (MIIT, 2017b; Sanderson, Hancock, & Lewis, 2017). As of 2017, only BYD and CATL have exceeded such production capacities, and Lishen plans to do so by 2020. China also has plans to set minimum production capacities for battery manufacturers. Although not yet official, China would like its local battery manufacturers to have a production volume of at least 3 to 5

GWh per year. These mandates and subsidy restrictions aim to spur the consolidation of small-player manufacturers, and rapidly increase economies of scale to help drive battery costs lower. In addition, there are tax exemptions for battery producers. The Ministry of Finance, since February 2015, exempts manufacturers of advanced batteries—including lithium-ion and nickel metal hydride, but excluding lead-acid—from the customary 4% consumption tax, which is analogous to purchase tax in the United States (Ministry of Finance, 2015). This has helped accelerate the production of batteries produced by BYD, CATL, and Lishen.

China has effectively promoted foreign investment in batteries for electric vehicles in several ways. One way is by restricting electric vehicle incentives to vehicles with batteries manufactured in China. For instance, South Korea-based companies LG, SDI, and SKI have been driven to China-based production in order for electric vehicles with their batteries to have access to government subsidies. These companies have either existing battery plants in China, in the case of SDI and LG, or joint ventures with China-based car manufacturing companies which is the case for SKI. In addition, in 2017, Tesla was in negotiation with the central China government to establish a large battery factory in China, possibly in the Shanghai area. A condition for such foreign companies is that they partner with China-based suppliers through joint ventures. China has indicated the possibility of easing joint-venture requirements over time.

Battery production developments in Europe

Although Europe has lagged other countries in battery production, as quantified above, a series of European and national measures aim to greatly expand battery production there. European policymakers are aiming to greatly expand battery cell production through the European Union Battery Alliance to better cover the value chain of the electric vehicles assembled there. In public remarks on the initiative, European Commission Vice President Maroš Šefčovič described the need for 10 to 20 battery factories of 1 GWh or more, at a1-billion-euro investment for each (European Commission, 2018). Financial support for the automotive industry to build battery production facilities ultimately could come from the European Fund for Strategic Investments (EFSI), launched by the European Commission and the European Investment Bank in 2015 to help deliver 315 billion euros in private investment (European Investment Bank, 2018; Autovista Group, 2017). We also note a number of initiatives underway in European member states.

Colocating battery production facilities near vehicle manufacturing helps save on logistics costs and supplier-automaker engineering collaboration. Through 2017, the largest electric vehicle battery production plant in Europe was the AESC plant in Sunderland, United Kingdom, that has made packs for the nearby production of the Nissan Leaf. Poland and Hungary have battery plants under construction from LG and Samsung SDI, respectively. For LG's plant in Poland, the factory is located in the LG cluster in Kobierzyce Commune near Wroclaw. The Samsung SDI plant in Hungary used to be a plasma display panel (PDP) plant and is located in Göd, north of Budapest. The two new European plants were implemented along existing infrastructure. They also take advantage of the highe wage-adjusted labor productivity (Eurostat, 2014). Both of these countries have actively pursued foreign direct investments.

In the Hungary case, the country has had 70 strategic cooperation agreements with top companies in 2016 and is seeking to become an automotive industry investment hub (Ésik, 2016; "Inauguration," 2017). Hungary also has offered a significant number of incentive options to battery suppliers and car manufacturers, including financial grants in the form of direct subsidies, job creation subsidies, and cofinanced tenders with the European Union. With regard to training and employment, grants for training, which include training subsidies and workshop establishment subsidies, as well as tax allowances are also provided (Ésik, 2016). For the SDI plant in Göd, Hungary reduced Samsung SDI's tax burden, and took on significant infrastructure developments to help spur SDI's investment of 300 million euros (Hungarian Government, 2017; Eckl-Dorna & Sorge, 2017).

Comparatively, LG is aiming to develop a larger battery plant in Poland with an initial capacity of about 6 GWh. To increase Poland's attractiveness as a location for foreign investors, tax preferences in special economic zones (SEZ) are offered to foreign investors. SEZs permit investors to conduct business activity and enjoy certain benefits after fulfilling certain conditions. These benefits include tax exemptions and public subsidies. When a company invests in SEZs, it can receive exemptions from income tax of 10% to 50% of the qualified investment expenditures or the value of two years' work of the newly hired employees, land with utility connections and infrastructure, and the possibility to purchase or lease property (Clifford Chance, 2017). Additionally, there is the chance to benefit from other investment incentives in the SEZ, including an exemption from real estate tax, investment grants from state administrative authorities, subsidies from local employment offices, and assistance from EU funds. In these arrangements, companies are given permits to operate in a SEZ and maintain newly created jobs for several years (Clifford Chance, 2017).

Countries with similar job growth and reindustrialization goals could similarly spur future battery factories. The Swedish company Northvolt is planning a facility in Skellefteå, about 800 kilometers north of Stockholm. The construction is expected to start in mid-2018 with a capacity of 8 GWh by 2020. According to company announcements, the plant is expected to increase in capacity to 32 GWh per year by 2023, which would amount to Europe's highest-production lithium-ion battery factory. The announcement indicates an investment of 4 billion euros ($4.7 billion), and eventually will support about 2,000 to 2,500 jobs at the factory in addition to 300 to 400 people at the research and development facility in nearby Västerås. (Reuters, 2017; The Local, 2017).

We note two Germany battery plant developments. The German Accumotive GmbH, a Daimler subsidiary, is expanding its battery production location in Kamenz, about 40 kilometers northeast of Dresden, Germany, and broke ground for its second factory in May 2017. The new production facility is scheduled to go into operation in mid-2018. With Daimler investing 500 million euros, lithium-ion batteries will be manufactured for Mercedes-Benz and Smart plug-in hybrid and battery electric models. Also, the Frankfurt-based TerraE Holding GmbH, an alliance of various German companies, is planning a large-scale lithium-ion cell manufacturing facility. From initial capacity of 5 GWh in 2020, TerraE has announced it will increase to 34 GWh at full production in 2028 and indicated the production facility will have 3,000 jobs (Golem, 2017; Mussig, 2017). The company intends to break ground by 2019 with a construction investment of 4 billion euros. The German government is supporting this investment with 5.5 million euros over 18 months to help research and develop this large-scale battery project (Higgelke, 2017).

Battery production developments in the United States

There have been several initiatives to help encourage the development of battery production facilities in the United States. These actions have been relatively limited compared to those in China and Europe. There are three major electric vehicle battery supplier plants in the United States—AESC in Smyrna, Tennessee; LG in Holland, Michigan; and the Tesla-Panasonic factory in Nevada. In addition, GM also has a battery pack assembly plant for the LG battery cells in Brownstown, Michigan. Federal stimulus funding in 2009 was used initially in several cases, and many states seek to encourage electric vehicle production and supplier production among other industrial activities.

At the federal level, the Obama administration in 2009 supported the development of advanced battery production in the United States. The federal support included $1.3 billion in federal stimulus funds to Michigan, including $151 million for LG's Holland plant to help develop an advanced battery industry (Haglund, 2009). Around the same time, Michigan used targeted battery plant incentive packages that awarded tax credits to offset business tax liability (Haglund, 2009). Nissan also used federal support for its battery production and electric vehicle manufacturing in and around Smyrna, Tennessee. Nissan used a $1.6 billion loan from the U.S. Department of Energy to retool its vehicle assembly and create its AESC battery production facility (Verprauskus, 2009).

At least five states competed to attract the Tesla Panasonic factory by offering tax incentives and cash grants tied to the prospects of job creation. The factory has an expected annual production capacity of 35 GWh when completed. Nevada was ultimately chosen, and direct rail access to Tesla's Fremont plant, a tax incentive package, renewable power sources for the plant, weather, direct Tesla sales access, and weather were factors. A combination of grants and tax abatements was offered by the state of Nevada, including $195 million in transferable tax credits, 20 years of sales-tax abatement worth approximately $725 million, and 10 years of property- and business-tax abatement worth approximately $332 million through 2034 (Hirsch, 2015).

Summary of battery production promotion actions

Table 4 summarizes several industrial policy actions that have helped the construction of major battery production facilities across the globe. The table includes a selection of the largest existing and announced such plants, the estimated battery production capacity, affiliated automobile companies, and examples of industry support policies. As shown, and as discussed more broadly above, a wide variety of actions are being used by national and local governments to spur the production of batteries to serve the development of electric vehicles and bring associated economic benefits. The examples in the table are a selection many dozens of facilities, existing and in the process of expansion, that serve the higher-production electric vehicle production models. We emphasize that the available information is not comprehensive, as complete details on all the incentives, tax breaks, and policy support actions are generally not publicly reported. For example, in many cases, our research finds details about the programs, but without clear descriptions about the exact amount of monetary support, how it is delivered—for example, whether through direct of future tax reductions—and the exact time frame in many cases. Regardless, the summary list in Table 4 helps to reveal, at least illustratively and with some details, the types and approximate magnitude of the policy support activities.

Table 4. Electric vehicle battery production plants, auto companies, and support actions

Facility and location	Battery production (future GWh) and auto companies	Examples of industrial policy support actions	Source
BYD *(Shenzhen, China)*	• 30 GWh (2020) • BYD	• Exemption from battery consumption tax • 228 million yen ($35 million) subsidies from central authorities for R&D of Li-ion batteries since 2015	Finance and Taxation (2015) BYD (2017)
CATL *(Ningde, China)*	• 50 GWh (2020) • BAIC	• Exemption from battery consumption tax • 85 million yen ($13 million) central special fund used to support innovation technology of new energy vehicle industry since 2015 • 100 million yen ($15 million) subsidies from central authorities for national key R&D program	Finance and Taxation (2015) NDWWW.CN (2016) EV Partner (2016)
LG *(Wroclaw, Poland)*	• 6 GWh (2018) • 15 GWh expansion (longer term) • Nissan, Mitsubishi, and Renault	• Exemption from income tax on activity conducted in Special Economic Zones (SEZ) • SEZ encouraged $350 million foreign direct investment from LG • Exemption from real estate tax (often offered by local communities to new foreign investors) • Investment grant from state authorities • Subsidies from local employment offices • Assistance in the form of EU funds • Additional utility and infrastructure benefits	Clifford Chance (2017) Eckl-Dorna and Sorge (2017)
SDI *(Göd, Hungary)*	• 3 GWh • BMW, Volkswagen	• Grants through subsidies, job creation subsidies, and EU cofinanced tenders to support $353 million investment. • Local subsidy granted by municipality • Development tax allowance (regional aid) • Training and workshop establishment subsidies	Ésik (2016) HIPA (2017)
LG *(Michigan, United States)*	• 3 GWh (year) • GM and Ford	• $151 million federal stimulus grant to finance 50% of $303 million plant • $125 million in state tax credits, with the condition of employing at least 300 people	Harger (2013) Haglund (2009)
Tesla/Panasonic *(Nevada, United States)*	• 35 GWh (2018) • Tesla	• Investment-dependable transferable tax credits • 20-year 100% sales tax abatement • 10-year 100% property tax abatement • 10-year 100% modified business tax abatement	Damon (2014)

INDUSTRIAL POLICY FOR VEHICLE ASSEMBLY

As previously discussed for battery production facilities, we investigate information on electric vehicle production facilities and the fiscal policy that has supported their creation and expansion. Within China, Europe, and the United States, substantial federal, regional, and local grants and tax incentives have been given to vehicle manufacturers to lower the barriers and cost in creating the new electric vehicle manufacturing facilities.

Table 5 summarizes several details about the location, electric vehicles produced, and government policy support for a selection of electric vehicle assembly facilities. The table clearly shows the vast scale of public investments being made to initiate electric vehicle production, with many subsidies and grants in the hundreds of millions of dollars. In addition, there are many local and regional grants and subsidies in the tens of millions of dollars. Several federal loans are larger, but these loans are repaid over time. Similar to Table 4 on battery production facilities, we provide the caveat that the table is incomplete, as it is difficult to know the full financial circumstances and exact value of all the tax breaks, grants, subsidies, and loans involved in these billion-dollar assembly plants. Nonetheless, because of the public funds and the large scale of these projects, a reasonable amount of information is released about the public expenditures that are linked to the production plants, as shown in the table.

Table 5. Selected electric vehicle assembly plants and support action

Facility and location	Vehicle models (production through 2017)	Examples of industrial policy support actions	Source
BAIC *(Beijing, China)*	• E-series (100,000+)	• 2,252 million yen ($346 million) subsidies in central and local fiscal funds since 2012	IAUTO (2017)
BMW *(Saxony, Germany)*	• BMW i3 (100,000) • BMW i8 (12,000)	• 17 million euros ($20 million) in national regional investment aid	Europäische Kommission (2014)
BYD *(Shenzhen, China)*	• BYD Tang (60,000) • BYD Qin (100,000)	• 3,317 million yen ($510 million) subsidies offered by central and local fiscal funds since 2012 • 10 yen per kWh subsidy granted for power battery recycling in Shenzhen since 2015	IAUTO (2017) Shenzhen Municipal Finance Bureau (2017)
GM *(Michigan, United States)*	• Chevrolet Volt (150,000) • Chevrolet Bolt (30,000)	• $600,000 tax abatement from the City of Detroit to build new logistics centers • $106 million federal grant to GM's Brownstown plant to assemble LG battery cells in packs	Wald (2009) Cwiek (2013)
Nissan *(Tennessee, United States)*	• Nissan Leaf (100,000)	• $1.6 billion federal loan • State grants, local property-tax incentives, tax and utility credits • $600 million in government subsidies since 2000 (includes $98 million county property tax abatement) • $53 million in job training or infrastructure grants since 2012 from the state of Tennessee	Reicher (2017) Verprauskus (2009)
Nissan *(Sunderland, United Kingdom)*	• Nissan Leaf (80,000)	• 21 million pound ($27 million) grant from UK Government • 197 million pound ($260 million) finance package from the European Investment Bank	Nissan Insider (2013)
Tesla *(California, United States)*	• Model S (200,000) • Model X (70,000)	• $565 million federal loan • $106 million tax break from state of California to support new assembly line for the Model 3	U.S. Department of Energy Loan Programs Office (2010) Lambert, 2016a Trefis Team, 2017

Based on the policies described above, and additional fiscal support, it appears quite clear that the most supportive policies to promote electric vehicle manufacturing have been implemented by China. The government in China, at both the central and local levels, has greatly subsidized the manufacture of electric vehicles. The fiscal subsidies are provided to the vehicle manufacturers by the central Ministry of Finance and the municipal finance bureaus. The value of subsidies to the manufacturers is based on electric vehicles' driving range per charge; they vary by region; and PHEVs typically have less incentive than BEVs. For example, BAIC received 2.25 billion yen (approximately $350 million) combining both central and local fiscal funds since 2012 (IAUTO, 2017).

The E-series, one of BAIC's most popular 2016 models, qualified for 44,000 yen ($6,800) per vehicle from the central Ministry of Finance and 22,000 yen ($3,400) per vehicle from Beijing Municipal Finance Bureau in 2017 (MIIT, 2017c; Beijing Municipal Finance Bureau, 2016). BYD has claimed about 3.3 billion yen ($500 million) in subsidies since 2012 (IAUTO, 2017). BYD Tang, one of the best-selling plug-in hybrid models by BYD, was eligible for 24,000 yen ($3,700) per vehicle from central Ministry of Finance and 12,000 yen ($1,800) per vehicle from Shenzhen Municipal Finance Bureau in 2017 (MIIT, 2017c; Shenzhen Municipal Finance Bureau, 2016).

As indicated in Table 5, there are several ways in which electric vehicle assembly has been promoted in Europe—at the European Union level, nationally, and locally. There is access to financial support in the form of subsidies from the European Investment Bank, as in the case of Nissan Leaf production plant in the United Kingdom. Further subsidies for battery cell production plants could be provided by the European Fund for Strategic Investments (EFSI), in the future. Relatedly, in mid-2017, German Chancellor Merkel signaled the prospect of financial support from the European Fund for Strategic Investments (EFSI) to support the auto industry (Delhaes, Menzel, & Buchenau, 2017). There is also a variety of policy support actions including tax exemptions on income or real estate tax, national and regional subsidies and specific subsidies for job creation, investment grants and other benefits such as utility and infrastructure development. For example, the Nissan UK facility for European Leaf production was linked with 21 million pounds ($27 million) from the UK government and a finance package from the European Investment Bank of up to 197 million pounds ($260 million) (Nissan Insider, 2013). Also, the BMW i-series manufacturing plant in Leipzig received 17 million euros national regional investment support (Europäische Kommission, 2014).

There are several relatively large electric vehicle production plants in the United States, and similar to in Europe, they were supported by a series of national and regional grants and subsidies. The electric vehicle plants established by GM, Nissan, and Tesla each have state grants, tax credits, and subsidies on the order of at least $100 million supporting their construction and expansion. The local support has tended to be in the tens of millions of dollars. There were also several federal loans that were much larger, including $1.6 billion for Nissan and $565 million for Tesla, but these were stimulus loans provided in 2009 (i.e., not expected to be repeated) and they have since been repaid. We note that similar financial support has been quite typical for new manufacturing plants for conventional combustion vehicles, but a comparison of these public funding packages for electric vehicle plants versus those is beyond the scope of our research.

IV. CONCLUSIONS

Based on the above assessment of the electric vehicle market and the associated battery production, we conclude here with a summary of findings regarding the industry dynamics and the positions of the major auto markets. Building from our identification of the underlying national and local policies in leading markets, we then draw a series of policy implications regarding how governments could better spur the electric vehicle and battery supply chain.

SUMMARY OF FINDINGS

The shift to electric vehicles amounts to a major growth opportunity for electric vehicles and especially electric vehicle battery technology. Based on the UBS (2017) teardown analysis, electric vehicles could reshape which industry players control the supply chain, including shifting more high-value power train parts to suppliers. Batteries are central to the shift, representing 31%–36% of the electric vehicles' content, even when the battery pack costs drop to $100–$130 per kilowatt-hour. This cost reduction presents an opportunity for cost parity with conventional vehicles by about 2025 and makes improving the battery pack a primary way companies—automakers, battery suppliers, or pairings of the two—can strategically compete. The automakers and suppliers that achieve higher volume faster will enable faster profitability in the 2020s.

The auto and battery supplier industries are signaling preparations for a massive scale up of electric vehicles through 2025. As introduced at the start of this paper, nearly all of the large global automakers are making strong statements about their commitment to electrification. Compiling just the quantifiable public announcements indicates automakers would surpass 13 million annual electric vehicle sales by 2025, up from 1.2 million in 2017, for an annual growth rate of 35%. Our summary of battery capacity announcements, although uncertain, is closely aligned with an annual growth rate of 35%. The automaker announcements amount to approximately 10% of global vehicle sales being electric in 2025, depending on overall global automobile market growth. This global average of 10% compares to 25% or greater for leading electric vehicle manufacturing companies. The announced auto industry electrification investments of more than $150 billion through 2025 help motivate this paper's research into where many of these investments are likely to go.

Developments to date in electric vehicle sales, production, and battery production show a high concentration in five regions. Figure 8 summarizes the broader dynamics of the industry developments, including a summary of electric vehicle sales, electric vehicle production, and electric vehicle battery production from 2010 through 2017 for the five main regions. The breakdown of those numbers as a percentage of the cumulative global electric vehicles, which amounted to about 3.2 million through 2017, is shown on right axis. As shown, some regions have seen greater market sales growth, whereas others have seen greater industrial production of electric vehicles, and prevalence of regional battery cell production for these electric vehicles varies. Electric vehicle sales and production are largely concentrated in China, Europe, Japan, and the United States. These four regions account for more than 97% of the sales, and 93% of the manufacturing, of electric vehicles. Overall, more than three quarters of all electric vehicle sales were manufactured in the same region in which they were sold. The figure also shows that China, Japan, and South Korea are major battery cell producers, accounting for approximately 90% of the electric vehicle battery cell production in the world.

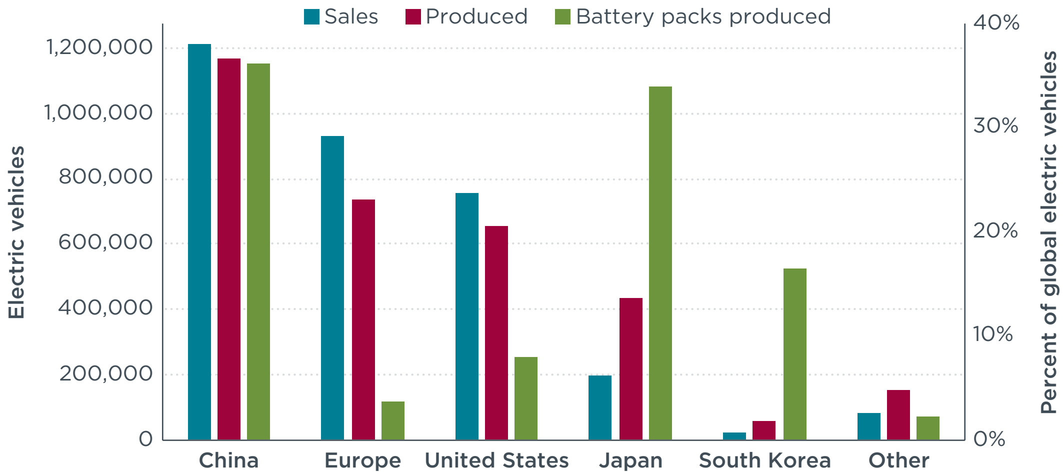


Figure 8. Electric vehicle sales, electric vehicles produced, and electric vehicle battery production by region through 2017, with percentage of global electric vehicles on right axis.

Some major electric vehicle markets are battery importers, and others are major exporters. The auto industry in Japan has disproportionately manufactured electric vehicles (more than 400,000, from 2010 through 2017) and their batteries (cells for more than 1 million electric vehicles), but the domestic electric vehicle market there has been comparatively limited. Similarly, in South Korea, the electric vehicle sales and production have been low, but electric vehicle battery production has been high, with cell production for more than 500,000 electric vehicles. The United States and Europe have been major manufacturers of electric cars, each with more than 600,000 produced, but these regions have largely imported the battery cells from elsewhere. What stands out the most in Figure 8 is China, as it is the largest market and has had comparatively little import or export of electric vehicles or battery cells. The China market now has the highest electric vehicle sales, electric vehicle production, and battery cell production for electric vehicles, now accounting for more than 36% of each of these globally through 2017.

POLICY IMPLICATIONS

Policy is the underlying driver for electric vehicle growth around the world. The associated electric vehicle policies in place help us make sense of these electric vehicle production results. Table 6 summarizes electric vehicle policy actions in most of the major national electric vehicle markets. Several vehicle sales and production statistics also are shown at the top of the table for the broader market context. As throughout this report, the data include only light-duty vehicles. The table includes a summary of the three major Asian markets, the two major North American markets, and also five major European markets for electric vehicles. The table is based on a similar table by Lutsey (2015) and includes updated information from the research discussed above to summarize the key industrial policy actions. The markets shown in the table account for the vast majority of global electric vehicle sales (93%), production (94%), and electric vehicle battery cell manufacturing (100%).

Table 6. Summary of government electric vehicle promotion actions in selected areas

Area	Action	China	United States	Germany	Japan	France	South Korea	United Kingdom	Canada	Norway	Netherlands
Vehicles	Vehicle sales in 2017 (million vehicles)	25	16	3.4	4.1	2.1	1.5	2.5	2.1	0.2	0.4
	Vehicle manufacturing in 2017 (million vehicles)	25	11	5.6	8.3	1.7	3.7	1.7	2.2	<0.1	0.2
Electric vehicles	Global 2010–2017 electric vehicle sales	39%	24%	4%	6%	4%	1%	4%	2%	6%	4%
	Global 2010–2017 electric vehicle production	37%	21%	13%	14%	5%	2%	2%	0%	0%	0%
	Electric vehicle sales 2017 (thousands)	579	195	53	52	37	14	45	19	62	9
	Electric vehicle production 2017 (thousands)	595	200	146	98	45	30	17	4	0	0
Industrial policy	Research and development support	X	X	X	X	X	X	X	X	X	X
	Battery cell or electric vehicle production incentive	X	/					X			
	Minimum battery production size incentive	X									
	Local manufacturing tax incentives	X	/	/	/	/	/	/	/		
	Battery production minimum capacity mandate	X									
	Vehicle incentives linked to domestic batteries	X									
Regulatory policy	Long-term efficiency or CO_2 standards	X	X	X	X	X	X	X	X	X	X
	Incentive provisions within efficiency regulations	X	X	X		X		X	X	X	X
	Electric vehicle deployment requirements	X	/						/		
	Goal for long-term transition to electric drive	/	/	/		X	/	X		X	X
Consumer support	Vehicle purchase incentive	X	X	X	X	X	/	X	/	X	X
	Government purchasing preferences	X	/	/	X	/	X	/	/	/	/
	Local registration, lottery, auction preference	X									
	High baseline fuel price (i.e., greater fuel savings)			X		X		X		X	X
	Annual vehicle fee exemption		/	X	X			/		X	X
	Discounted/free electric charging	/	/	/	X			/	/	X	X
	Preferential lane (e.g., bus, HOV lane) access	/	/	/						X	X
	Reduced roadway tax or tolls				X			X		X	X
	Preferential parking access	/	/	/		/		/	/	/	/
	Public outreach campaign	/	/	/	/	/		X	/	X	/
Charging infrastructure	Carbon pricing scheme	X	/	X	X	X		X	/	X	X
	Low carbon fuel incentive for electricity providers		/					/	/		
	Public charging network funding	X	/	X	X	X	X	X	/	X	X
	Home charging equipment tax incentives		/			X	/		/		

Note. Vehicle statistics are for light-duty passenger vehicles; "X" denotes national program; "/" signifies smaller local or regional program.

Growing the electric vehicle market requires a broad mix of policy actions. The broader finding from Table 6, as found in many studies, is that markets with the highest electric vehicle uptake have a rich portfolio of support actions to break down electric vehicle barriers and develop the market. Most of the 10 countries shown have implemented many of the same actions to promote the electric vehicle market through bottom-up actions with regulatory policy, consumer incentives, and charging infrastructure. These actions address the associated electric vehicle market barriers of limited electric vehicle supply, high upfront technology cost, and recharging convenience. However, Table 6 also shows that governments have not equally promoted electric vehicles from an industrial policy perspective. China stands out as having more policies to address barriers in the industrial supply chain, in particular by promoting battery production.

Much of the growth in high-volume battery production is likely to be concentrated in China. Overall, based on industry announcements, we find that battery capacity is expected to increase by a compounded 35% per year from 2017 through 2022. As analyzed above, China as of 2017 accounts for half of the global electric vehicle battery cell production capacity and the number of light-duty electric vehicles supplied with batteries. Our tally of all the announced 2017–2022 battery plant developments suggests that China is likely to maintain a similar fraction of global electric vehicle battery production, accounting for more than half of electric vehicle battery capacity through 2022. We also find that announced battery production in Europe would account for 17% of the global battery capacity, compared to 15% in South Korea, 12% for the United States, and just 4% in Japan.

What largely separates the top global markets is China's strong central planning with concerted policy follow-through on its market and industrial policies. The policies are developed to meet five-year plans related to China's automotive industry strategy and battery development plans. China has demonstrated the most comprehensive electric vehicle support package specifically by linking its electric vehicle market policies to its vehicle industry regulations and to its battery supply chain policy. The approach therefore has three reinforcing policies that reduce the chance of any constraints in its transition to electric drive. The China-related electric vehicle findings from Figure 8 can be connected directly to policy in each area:

» *Electric vehicle sales*. To meet the volume targets, China has the most robust system of consumer-driven electric vehicle policy, with substantial financial incentives, strong vehicle registration policy at the local level, and extensive charging infrastructure (Yang et al., 2016; Hall, Cui, & Lutsey, 2017; Hall & Lutsey, 2017b).

» *Electric vehicles produced*. To promote electric vehicle deployment, China has one of the most extensive electric vehicle deployment requirements in the world. The New Energy Vehicle mandate, finalized in 2017, virtually assures that annual light-duty electric vehicle deployment in China will increase from approximately 600,000 in 2017 to more than 1 million by 2019 or 2020 (Cui, 2018).

» *Electric vehicle supply chain*. To ensure an expanding battery supply chain, China's policies include substantial per-vehicle incentives for battery manufacturers, with eligibility linked to China-based production and minimum battery plant production that is over 8 GWh in annual capacity, as described above. There are no such policies in place elsewhere.

A series of European policy decisions present an opportunity to launch Europe's electric vehicle market. Europe's policy developments related to electric vehicles have been significant, but not as robust as those in China. Several 2018–2019 policy decisions will shape the European auto industry's future for 2025–2030, the time frame wherein electric vehicles are expected to reach cost parity with conventional vehicles. Stronger CO_2 requirements and electric vehicle sales requirements at the EU-level, reinforced by taxation policies and electric vehicle sales quotas at the member state level, would provide a foundation for more substantial electric vehicle investments. Complementary local policies such as low emission zones that steer vehicles toward electric to meet local air quality and climate change goals would also reinforce the transition. Addressing the lack of industrial policy to ensure electric vehicle battery plants get built could include a combination of actions. Such actions could include partnerships between European automakers and battery developers to construct much larger battery cell manufacturing plants, for example through the EU Battery Alliance, with the provision of ample investment funds, loan guarantees, and tax breaks.

Compared to the other leading global auto markets, industry developments to prepare for a shift to electric vehicles in the United States are in more of an uncertain position. Sustained and stronger policies would better promote the electric vehicle consumer market and the associated battery production. The United States is the third-largest electric vehicle market, after China and Europe, and most of its high-selling electric vehicle models (e.g., by Chevrolet, Nissan, and Tesla) are produced in the United States. However, beyond Panasonic-Tesla battery production in Nevada, the prospects for large battery production facilities in the United States are unclear. The present U.S. regulations would require only 2%–5% of new vehicles in 2025 be plug-in electric (U.S. EPA, NHTSA, & CARB, 2016), and those standards are under review to potentially be weakened. Even the California ZEV regulation would require that only about 8% of new vehicles sold be plug-in electric or fuel cell there (CARB, 2017). Committing to consistent long-term efficiency standards with stronger ZEV requirements by California and nine other U.S. states through 2030 would help address the inconsistent policy signals.

The development of electric vehicle manufacturing capacity in other countries is less clear. A major question that arises from this research is whether governments beyond China, Europe, and the United States can develop comprehensive electric vehicle promotion policies to follow a similar growth trajectory. Ultimately most manufacturing ends up in or near the large auto sales markets. For example, Japan-based Nissan and its battery supplier AESC expanded their manufacturing to include major production facilities in the United States and in the United Kingdom to serve the North American and European electric vehicles markets, respectively. Major auto markets like Brazil, Canada, India, and Mexico each have vehicle manufacturing of between 2 and 5 million vehicles annually; however, they have comparatively low electric vehicle production. If countries like these and others seek the same clean air, energy independence, climate change mitigation, and industrial growth goals as China, Europe, and the United States, they could adopt similar policies, tailored to their own markets. Not doing so puts major automobile-manufacturing countries at risk of losing out on being a part of the growing electric vehicle industry and supply chain.

Based on all these developments, there is a broad global competition underway. There is a power play in the works, as governments seek to gain from the transition to electric vehicles with a series of supportive policies. The competition is among countries and companies to be a key part of the economic and market growth of electric vehicles. Of course, the development of electric vehicles and their batteries is not a zero-sum game. The auto manufacturing and battery leaders are global, looking for high production scale across multiple markets. With more countries moving forward with similar policies to break down consumer and supply chain barriers, each market will more easily reach its goals for zero-emission vehicles. To the extent that many governments send consistent signals, and global companies move to greater scale, the quicker all markets can make the transition to electric and reap the accompanying environmental and economic benefits.

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