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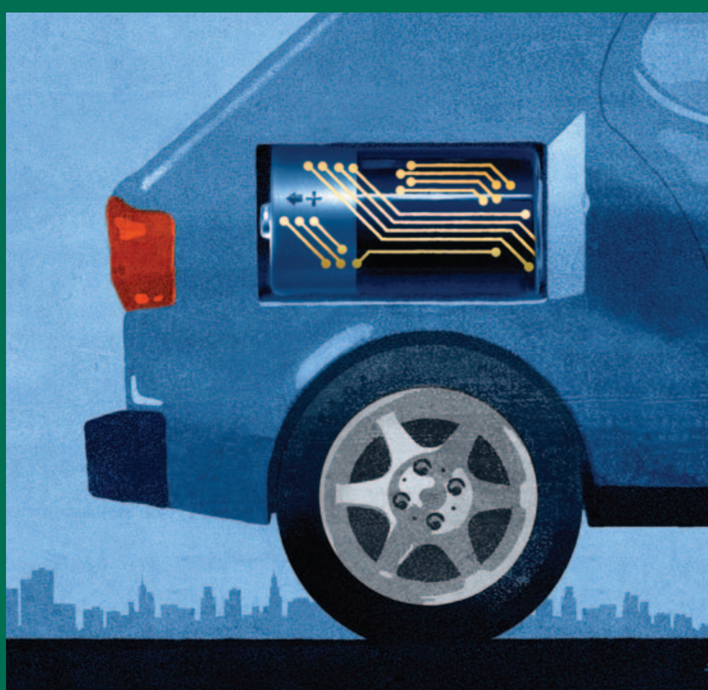
Batteries for Electric Cars

Challenges, Opportunities, and the Outlook to 2020



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Batteries for Electric Cars

Challenges, Opportunities, and the Outlook to 2020

What impact will the development and cost of various types of batteries have on the emerging market for electric cars? How much progress can we hope to see in the next decade, and what critical barriers will need to be overcome along the way?

The automotive industry's quest to limit its impact on the environment and transform automotive mobility into a sustainable mode of transportation continues at high intensity, despite the current economic crisis. In an earlier report, we analyzed the technical and cost tradeoffs of competing alternative power-train technologies.[1] In this companion piece, we address the two principal variables in our analysis of the developing market for electric cars: the technical attributes and the costs of lithium-ion batteries for electric-vehicle applications.

In assessing these variables, we drew on The Boston Consulting Group's extensive work with automotive OEMs and suppliers around the world and on a detailed analysis of the relevant intellectual-property landscape. We also created a battery cost model that allows us to project future costs. In addition, we conducted more than 50 interviews with battery suppliers, automotive OEMs, university researchers, start-up companies working on leading-edge battery technologies, and government agencies across Asia, the United States, and Western Europe.

In this report, we explore four main questions: What technological challenges must be overcome in order for lithium-ion batteries to meet fundamental market criteria? As battery technologies reach maturity, what might their cost profiles look like? What will electric vehicles' total cost of ownership (TCO) amount to? And how are industry participants likely to align themselves as they jockey for position in the evolving market?

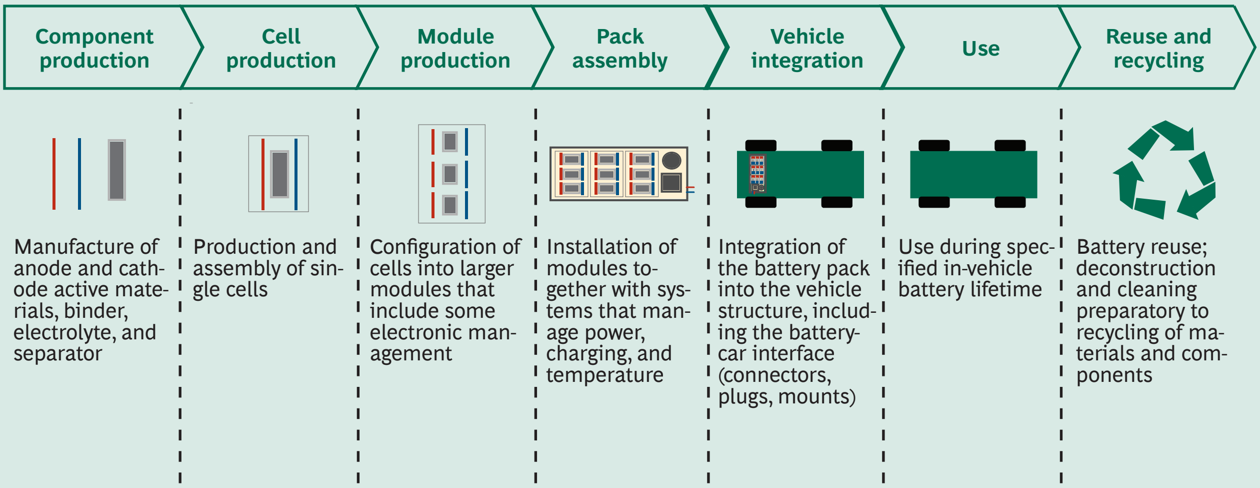
The Current State of Electric-Car Battery Technology

The value chain of electric-car batteries consists of seven steps: component production (including raw materials); cell production; module production; assembly of modules into the battery pack (including an electronic control unit and a cooling system); integration of the battery pack into the vehicle; use during the life of the vehicle; and reuse and recycling. (See Exhibit 1.) In this report we focus on the first four steps, which make up the manufacture of battery packs for use by OEMs.

Lithium-ion batteries comprise a family of battery chemistries that employ various combinations of anode and cathode materials. Each combination has distinct advantages and disadvantages in terms of safety, performance, cost, and other parameters. The most prominent technologies for automotive applications are lithium-nickel-cobalt-aluminum (NCA), lithium-nickel-manganese-cobalt (NMC), lithium-manganese spinel (LMO), lithium titanate (LTO), and lithium-iron phosphate (LFP). The technology that is currently most prevalent in consumer applications is lithium-cobalt oxide (LCO), which is generally considered unsuitable for automotive applications because of its inherent safety risks. All automotive battery chemistries require elaborate monitoring, balancing, and cooling systems to control the chemical release of energy, prevent thermal runaway, and ensure a reasonably long life span for the cells.

1. See *The Comeback of the Electric Car? How Real, How Soon, and What Must Happen Next,* BCG Focus, January 2009.

Exhibit 1. The Value Chain for Electric-Car Batteries Comprises Seven Steps



Source: BCG analysis.

In this paper we do not address the impact of new battery chemistries, lithium-based or otherwise, because none of the players we interviewed expect that batteries based on new chemistries will be available for production on a significant scale by 2020. However, there is increasing interest and activity, particularly among university research laboratories, in exploring new electrochemical mechanisms that might boost the specific energy and performance of future batteries. Patent filings related to energy storage increased 17 percent per year from 1999 through 2008, twice as fast as during the previous ten years and some ten percentage points faster than overall patent growth during the same period. Of the energy-storage patents filed in China, Japan, the United States, and Western Europe in 2008, lithium-ion technologies accounted for 62 percent, having grown at 26 percent per year from 2005 through 2008. Lithium-ion patents relating to electrode chemistry, materials, and electrolytes were filed principally by universities, whereas those relating to pack structure, cooling, and controls were filed mainly by OEMs and suppliers. LFP technology has been the focus of at least twice as much patent activity as LTO technology and four times as much as NMC technology, most likely because of LFP's promising safety characteristics and higher usable capacity.

The recent explosion in innovation is driven by the need to break some fundamental compromises in battery technology. On the technical side, competing lithium-ion technologies can be compared along six dimensions: safety; life span (measured in terms of both number of charge-and-discharge cycles and overall battery age); performance (peak power at low temperatures, state-of-charge measurement, and thermal management); specific energy (how much energy the battery can store per kilogram of weight); specific power (how much power the battery can store per kilogram of mass); and cost. (See Exhibit 2.) On the business side, high costs remain the major hurdle. The challenge will be to reduce manufacturing costs through scale and experience effects as market volumes expand. We discuss each of these hurdles in some detail below; we also address charge time, which does not vary substantially among battery technologies but remains a significant performance challenge for all of them.

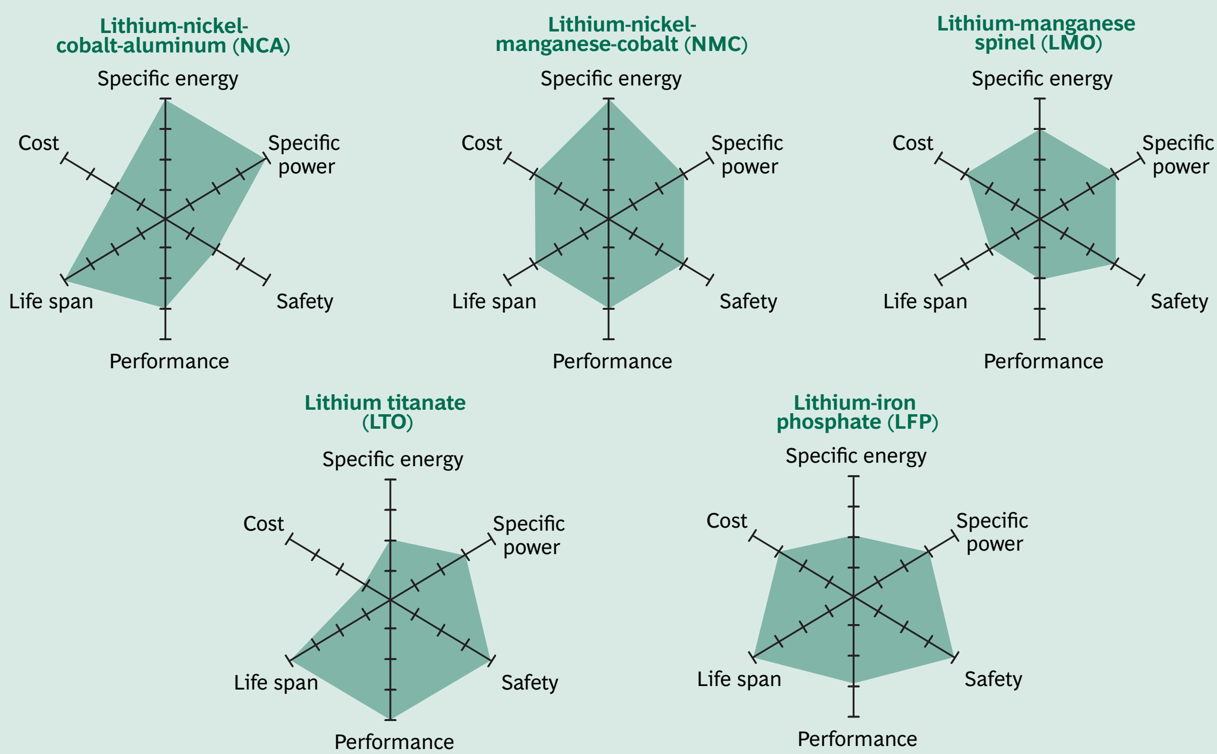
Currently, as Exhibit 2 shows, no single technology wins along all six dimensions. Choosing a technology that optimizes performance along one dimension inevitably means compromising on other dimensions. NCA technology, for example, is a fairly high-performance solution but presents safety challenges, whereas LFP technology is safer at the cell level but provides a low specific energy. Interviews we conducted during the course of this study suggest that multiple chemistries are likely to coexist for some time as technologies evolve and intellectual-property ownership gets sorted out. Any player that succeeds in breaking some of the inherent compromises among current technologies will gain a significant advantage in the marketplace. Meanwhile, all OEMs and suppliers will have to manage the tradeoffs among the six key performance parameters.

Safety. Safety is the most important criterion for electric-car batteries. Even a single battery fire could turn public opinion against electric mobility and set back industry development for months or years. The main concern in this area is avoiding thermal runaway—a positive-feedback loop whereby chemical reactions triggered in the cell exacerbate heat release, potentially resulting in a fire. Thermal runaway can be caused by an overcharged battery, too-high discharge rates, or a short circuit. Chemistries that are prone to thermal runaway, such as NCA, NMC, and LMO, must be used in conjunction with system-level safety measures that either contain the cells or monitor their behavior. Such measures include a robust battery box, a very efficient cooling system (to prevent the early stages of thermal runaway), and precise state-of-charge monitoring and cell-discharge balancing. OEMs and suppliers need to decide which is preferable: inherently safer chemistries, such as LFP and LTO, or chemistries that offer higher energy but are less safe, such as NCA, which must be used in conjunction with rigorous safety systems.

While battery safety is indisputably a valid concern, it is useful to put this concern in context by recalling the significant safety challenges originally associated with the internal combustion engine (ICE) and with gasoline storage, which were largely overcome through improvements in design and engineering.

Life Span. There are two ways of measuring battery life span: cycle stability and overall age. Cycle stability is the number of times a battery can be fully charged and discharged

Exhibit 2. There Are Tradeoffs Among the Five Principal Lithium-Ion Battery Technologies



Source: BCG research.
Note: The farther the colored shape extends along a given axis, the better the performance along that dimension.

before being degraded to 80 percent of its original capacity at full charge. Overall age is the number of years a battery can be expected to remain useful. Today's batteries do meet the cycle stability requirements of electric cars under test conditions. Overall age, however, remains a hurdle, in part because aging accelerates under higher ambient temperatures. It is as yet unclear how fast various kinds of batteries will age across a range of automotive-specific temperature conditions.

To manage these uncertainties, OEMs are specifying batteries of sufficient size to meet electric cars' energy-storage needs over the typical life of a vehicle. Most automotive manufacturers are planning for a ten-year battery life span, including expected degradation. For example, an OEM whose electric car nominally requires a 12-kilowatt-hour (kWh) battery is likely to specify a 20-kWh battery instead, so that after ten years and 40 percent performance degradation, the battery will still have sufficient energy capacity for normal operation. Of course, this approach increases the size, weight, and cost of the battery, adversely affecting the business case for electric cars.

OEMs can consider other options. For instance, they might choose to install smaller batteries with a shorter life span and plan to replace them every five to seven years, possibly under a warranty program. Taking this approach would allow OEMs to use smaller batteries initially, upgrading them as the technology continues to advance. Battery-leasing business models, such as those proposed by Think, a manufacturer of small city cars, and Better Place, a start-up provider of battery infrastructure, also allow for shorter-lived batteries. These models decouple the battery's life span from the vehicle's life span and remove up-front battery costs.

OEMs might choose to install smaller batteries with a shorter life span and replace them every five to seven years.

Performance. The expectation that the owner of an electric vehicle should be able to drive it both at blisteringly hot summer temperatures and at subzero winter temperatures poses substantial engineering challenges. Batteries can be optimized for either high or low temperatures, but it is difficult to engineer them to function over a wide range of temperatures without incurring performance degradation. One solution might be for OEMs to rate batteries for particular climates. For example, batteries optimized for performance and endurance in cold climates would rely on heating and insulation, whereas those designed for hot climates would use electrolytes and materials that allow high-temperature storage. The differences between these two battery designs would be more substantial than the current distinction between, for example, cold-weather and warm-weather tires. But this approach would result in batteries with higher functionality, albeit under limited conditions. However, because climate-specific batteries would hinder vehicles' mobility across regions, OEMs are likely to prefer a performance disadvantage or higher overall system costs in order to avoid such restrictions.

Specific Energy and Specific Power. The specific energy of batteries—that is, their capacity for storing energy per kilogram of weight—is still only 1 percent of the specific energy of gasoline. Unless there is a major breakthrough, batteries will continue to limit the driving range of electric vehicles to some 250 to 300 kilometers (about 160 to 190 miles) between charges. Battery cells today can reach nominal energy densities of 140 to 170 watt-hours per kilogram (Wh/kg), compared with 13,000 Wh/kg for gasoline. The specific energy of the resulting battery pack is typically 30 to 40 percent lower, or 80 to 120 Wh/kg. Even if that energy density were to double in the next ten years, battery packs would still store only some 200 Wh/kg of weight. Assuming that the battery weighs around 250 kilograms—about 20 to 25 percent of the total weight typical of small cars today—that doubling of energy density would give an electric car a range of some 300 kilometers (about 190 miles).

Specific power, or the amount of power that batteries can deliver per kilogram of mass, is addressed relatively well by current battery technologies. Specific power is particularly important in hybrid vehicles, which discharge a small amount of energy quickly. In electric vehicles, specific power is less important than specific energy. Manufacturers have established design parameters for electric-vehicle batteries to optimize the tradeoff between specific energy and specific power. Currently, batteries' performance in terms of specific power equals or exceeds that of

ICEs. So researchers are concentrating their efforts on increasing batteries' specific energy for given power levels.

Charging Time. Long charging times present another technical challenge and a commercial barrier that must be addressed. It takes almost ten hours to charge a 15-kWh battery by plugging it into a standard 120-volt outlet. Fast charging methods that employ more sophisticated charging terminals can reduce this time significantly. For example, charging by means of a 240-volt outlet with increased power (40 amps) can take two hours, while charging at a commercial three-phase charging station can take as little as 20 minutes. These charging systems do come at an additional cost and weight, as they require enhanced cooling systems on board the vehicle. Battery-swap methods, such as the models contemplated by Better Place, promise to provide a full charge in less than three minutes. But such approaches need OEMs to agree to pack standardization requirements and would entail additional logistical complexity.

Without a major breakthrough in battery technologies, fully electric vehicles that are as convenient as ICE-based cars—meaning that they can travel 500 kilometers (312 miles) on a single charge and can recharge in a matter of minutes—are unlikely to be available for the mass market by 2020. In view of the need for a pervasive infrastructure for charging or swapping batteries, the adoption of fully electric vehicles in 2020 may be limited to specific applications such as commercial fleets, commuter cars, and cars that are confined to a prescribed range of use. Of course, range-extender vehicles, which combine an electric power train with an ICE, overcome the range and infrastructure limitations of fully electric vehicles, but at the increased cost of the ICE.

Fully electric vehicles as convenient as ICE-based cars are unlikely to be available for the mass market by 2020.

The Cost Challenge

The United States Advanced Battery Consortium has set a cost target of $250 per kWh. But even if battery makers can meet the technical challenges outlined above, battery cost may remain above that target. Clearly, the cost of batteries will play a critical role in determining the commercial viability of electric cars. Estimates of current and future cost levels vary widely and are further complicated by a lack of clarity about which cost, precisely, is being estimated. Is it the cost of an individual cell, of a battery pack sold to an OEM, or of a replacement battery sold to a consumer? Because the cell represents some 65 percent of the cost of the battery pack, and because OEM markups can add another 35 to 45 percent to the pack price, these distinctions are important.

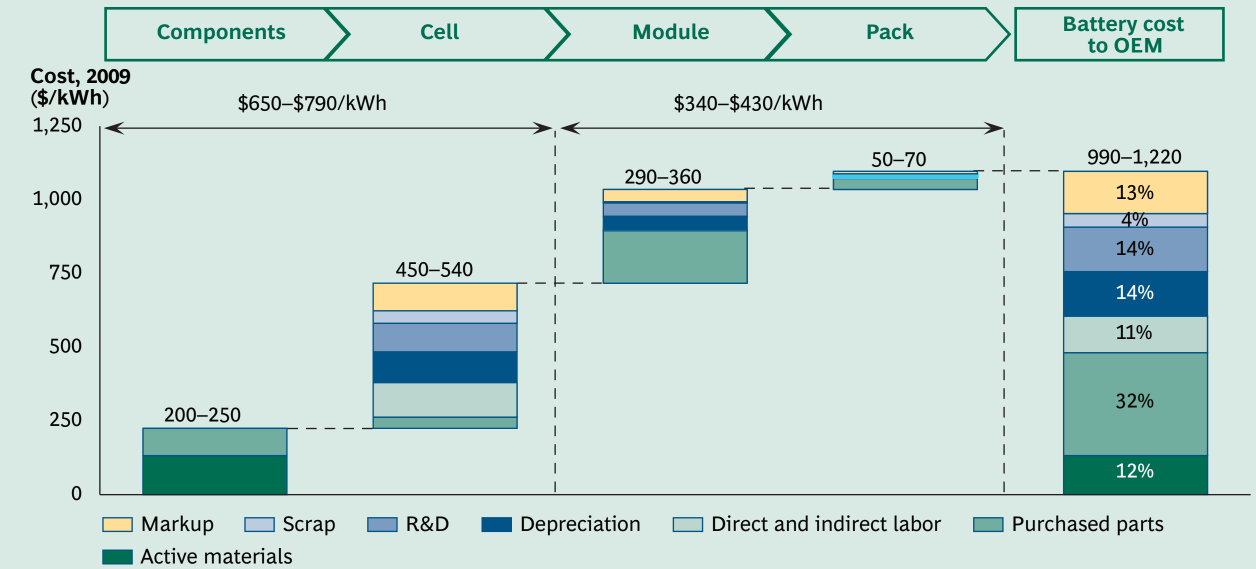
Current Costs and Forecasting Methodology. Most sources estimate the current cost of an automotive lithium-ion battery pack, as sold to OEMs, at between $1,000 and $1,200 per kWh. Citing the current cost of consumer batteries (about $250 to $400 per kWh), they further predict that this price tag will decline to between $250 and $500 per kWh at scaled production. However, consumer batteries are simpler than automotive batteries and must meet significantly less demanding requirements, especially regarding safety and life span. Nonetheless, $250 per kWh persists as the cost goal for an automotive battery pack. Given current technology options, we see substantial challenges to achieving this goal by 2020.

To forecast battery costs, we constructed a line-item model of the individual component costs involved in making a battery in 2009 and assigned variables likely to influence each component cost under an assumed level of production. The 2009 cost structure includes a complete pack-level bill of materials, direct and indirect plant labor, equipment depreciation, R&D, scrap rates, and overhead markup. (See Exhibit 3.)

We classified each component cost as either dependent on battery production volumes or independent of them. Our forecast of the evolution of volume-dependent costs assumes the acquisition of industry experience and increasing automation. Volume-independent costs include raw materials, labor rates, and general machinery. We estimate that some 70 percent of cell costs and 75 percent of battery pack costs are volume dependent, effectively creating a cost "glass floor" for current battery technology. We took into consideration various chemistries, various cell-module-pack configurations, and production costs in different countries.

For purposes of reference and comparison, we assumed a typical suppli-

Exhibit 3. Batteries Cost OEMs About $1,100 per kWh at Low Volumes



Sources: Interviews with component manufacturers, cell producers, tier one suppliers, OEMs, and academic experts; Argonne National Laboratory; BCG analysis.
Note: Exhibit shows the nominal capacity cost of a 15-kWh NCA battery and assumes annual production of 50,000 cells and 500 batteries, as well as a 10 percent scrap rate at the cell level and a 2 percent scrap rate at the module level. Numbers are rounded.

er of 15-kWh NCA batteries using modestly automated production to make 50,000 cells and highly manual assembly to produce 500 battery packs. These assumptions are in line with currently observed trial production levels.

We estimate that this supplier's 2009 cell costs—$650 to $790 per kWh—account for approximately 65 percent of its total cost for the battery pack. Costs to an OEM for a 15-kWh range-extender pack would be between $990 and $1,220 per kWh—or more than $16,000. Cost per kWh for smaller batteries, such as a 2-kWh pack for a more traditional, hybrid car, would be higher, for two reasons. First, some pack-level costs, such as power management systems and wiring harnesses, are somewhat independent of battery size; second, smaller batteries are optimized for power rather than energy storage capacity. In this paper we focus on larger batteries, as these are most relevant for cars that are primarily electrically driven.

Scrap. One area in which there is clear opportunity to reduce costs is scrap rates, where we observed a broad range of performance in the relatively manual production processes in use in 2009. Automotive-industry cost structures, margins, and standards mandate scrap rates of less than 0.1 percent, but we noted actual scrap rates varying from 10 percent to as high as 30 to 60 percent. Manufacturers incurring the higher scrap rates are likely to have battery costs in the range of $1,500 to $1,900 per kWh.

Usable Capacity and Markup. The values discussed above all assume nominal battery capacity, which can be significantly higher than actual, usable capacity. Depending on the chemistry of the battery, its usable capacity over a ten-year life span is in the range of only 50 to 80 percent of its nominal capacity. Furthermore, the costs described here are costs to OEMs. Assuming typical OEM and dealer margins, the price that end users will pay for batteries is likely to be 40 to 45 percent higher than OEMs' purchase price, or some $1,400 to $1,800 per kWh. OEMs and dealers may subsidize this markup somewhat during launch periods, but we believe that in the long term they will need to collect it in order to compensate for marketing and operating the battery throughout its life cycle.

Chemistries. Differences in component-level cost structures for materials are not always reflected in differences between cell-level costs. For instance, consider two lithium-ion technologies, NCA and LFP. Although material costs for NCAs are some 50 percent higher than those for LFPs because of the high cost of nickel and cobalt, this disadvantage is largely offset by the fact that NCAs need smaller amounts of active materials, thanks to their 30 percent higher specific-energy capacity and higher voltage (3.6 volts rather than 3.2 volts). Nonetheless, the competition between the two technologies could turn in favor of LFPs, given their higher usable capacity.

Active cathode materials (NCA, LFP, and the like) and purchased parts account for nearly half of battery costs at both the cell and pack levels. While economically viable lithium supplies are somewhat concentrated geographically—as are the companies that mine the material—we do not foresee supply constraints that would significantly affect lithium prices. Further, because lithium represents less than 2 percent of cell-level costs, any potential price increase would have only a limited impact.

The Outlook for Battery Costs to 2020. Battery costs will decline steeply as production volumes increase. Individual parts will become less expensive thanks to experience and scale effects. Equipment costs will also drop, lowering depreciation. Higher levels of automation will further trim costs by increasing quality, reducing scrap levels, and cutting labor costs. However, some 25 percent of current battery costs—primarily the costs of raw materials and standard, commoditized parts—are likely to remain relatively independent of production volumes and to change only modestly over time.

In forecasting the market for batteries, we assumed that 26 percent of the new cars sold in 2020—or some 14 million cars—will have electric or hybrid power trains. We assume that all range-extender and fully electric vehicles will have lithium-ion batteries, as will some 70 percent of the hybrids sold. The remaining 30 percent of hybrids—the smaller and lower-cost vehicles—will still use the nickel-metal hydride (NiMH) batteries popularized by first-generation hybrid vehicles, such as the Toyota Prius. In total, some 11 million new cars sold in 2020 will be equipped with lithium-ion batteries.

The cost target of $250 per kWh is unlikely to be achieved at either the cell level or the battery pack level by 2020.

In forecasting battery costs, we anticipated that active materials and purchased parts will make up nearly half of overall battery costs in 2020, while processing and depreciation will each represent another 10 percent of costs, and R&D, markup, and SG&A will together account for the remaining 30 percent. We also assumed highly automated, high-volume production, especially at the cell level. And we assumed an annual production volume for an individual supplier of approximately 73 million cells and 1.1 million battery packs.

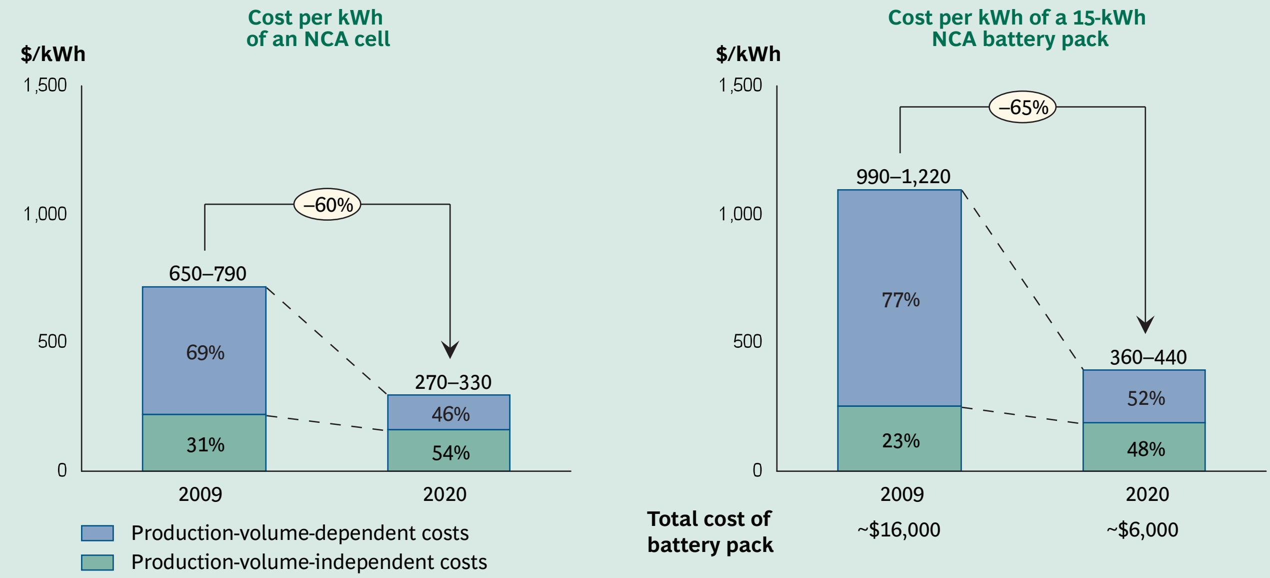
Notably, battery cost is not substantially sensitive to manufacturing location. Our model assumes production in South Korea. However, because of the low labor content of battery production, making batteries in the United States would increase costs by just 6 percent, while making them in China would reduce costs by only about 8 percent.

Our analysis suggests that from 2009 to 2020, the price that OEMs pay for NCA batteries will decrease by roughly 60 to 65 percent. (See Exhibit 4.) So a nominal-capacity 15-kWh NCA battery pack that currently costs $990 to $1,220 per kWh will cost $360 to $440 per kWh in 2020, or approximately $6,000 for the battery pack. The price to consumers will similarly fall, from $1,400 to $1,800 per kWh to $570 to $700 per kWh. Underlying these falling prices will be a parallel decline in the cost of cells, to just $270 to $330 per kWh. However, the cost of cells will fall less rapidly than the cost of battery packs because some 30 percent of cell costs are independent of production volume.

We conclude, therefore, that the cost target of $250 per kWh is unlikely to be achieved at either the cell level or the battery pack level by 2020—unless there is a major breakthrough in battery chemistry that leads to fundamentally higher energy densities without significantly increasing the cost of either battery materials or the manufacturing process.

The Size of the Battery Market. In our earlier report on the electric car, we modeled the likely market penetration of competing power-train technologies in 2020 for China, Japan, the United States, and Western Europe under three market-development scenarios: slowdown, steady

Exhibit 4. Battery Costs Will Decline 60 to 65 Percent from 2009 to 2020



Sources: Interviews with component manufacturers, cell producers, tier one suppliers, OEMs, and academic experts; Argonne National Laboratory; BCG analysis.
Note: Exhibit assumes annual production of 50,000 cells and 500 batteries in 2009 and 73 million cells and 1.1 million batteries in 2020. Numbers are rounded.

pace, and acceleration. That analysis led us to forecast that mild and full hybrids and electric vehicles would together achieve sales penetration of between 11 and 42 percent of those markets under the steady-pace scenario, with a likely overall penetration of 26 percent.[2]

We continue to endorse that forecast for 2020. Although the current economic crisis and the recent drop in oil prices might appear to mitigate strong market enthusiasm for alternative technologies, interest in long-term sustainability remains keen in the car-buying public as well as among governments and their regulatory bodies. We anticipate that these groups will continue to encourage the development of these technologies; also, it is reasonable to assume that oil prices will continue to rise over the medium to long term.

We anticipate that the approximately 14 million electric cars forecast to be sold in 2020 in China, Japan, the United States, and Western Europe will comprise some 1.5 million fully electric cars, 1.5 million range extenders, and 11 million hybrids. In that same year, the market for electric-car batteries in those regions will be worth some $25 billion. This burgeoning market will be about triple the size of today's entire lithium-ion-battery market for consumer applications such as laptop computers and cell phones.

This forecast applies to all components sold to OEMs, from raw commodities through the complete battery pack; it does not apply to the end-user market for batteries. If the acceleration scenario rather than the steady-pace scenario were to prevail, the market for electric-car batteries could reach $60 billion in 2020. However, if governmental economic support were to fall short of our expectations, the market would grow more slowly, reaching just $5 billion.

Charging-Infrastructure Costs. Charging infrastructure is another major component of electric vehicles' operating costs. We estimate the total cost of the installed charging infrastructure through 2020 at approximately $20 billion—about 40 percent in the United States, 30 percent in Europe, and 30 percent in the rest of the world. Some 60 percent

2. The mild hybrid contains a small electric motor that provides a start-stop system, regenerates braking energy for recharging the battery, and offers acceleration assistance. The full hybrid features both a larger battery and a larger electric motor, giving the car electric launching, electric acceleration assistance, and electric driving at low speeds.

($12 billion) of this cost will fund the creation and support of public charging infrastructure, which will need to be financed (at least initially) by governments, power companies, or private contractors.

The number of stations needed per vehicle and the cost of constructing each one are often cited as the key determinants of the total cost of the charging infrastructure. In our view, however, charging profiles and vehicle mix are also central to the calculation. For instance, vehicle owners in the United States and Japan are more likely than owners in Europe to have access to cheaper home charging stations. Furthermore, owners in the United States are more likely than Europeans to purchase range extenders. Because these vehicles can operate longer before recharging, they require fewer charging stations than fully electric vehicles and therefore entail lower infrastructure costs.

We estimate the total increase in electricity demand created by all the electric vehicles on the road in 2020 at less than 1 percent. This increase is not likely to require additional power-generation capacity in the short term. However, even if electric-vehicle sales stabilized at only 3 to 5 percent of overall market share, the number of electric vehicles on the road between 2020 and 2030 would drive up the demand for electricity by as much as 1 percent per year. In response, power companies might need to increase capacity. In the short term, local utilities may have to upgrade some segments of the grid to handle an increased load in areas where large numbers of electric vehicles are frequently charged.

Total Cost of Ownership. In the short to medium term, early adopters and government credits are likely to drive demand for electric vehicles. However, by 2020, mass-market buyers will consider the TCO profile of electric vehicles versus ICE-based vehicles when making their purchase decisions. These consumers will weigh electric vehicles' savings (generated by lower operating costs relative to gasoline) against higher up-front purchase prices.

Surveys suggest that purchasers want to break even on the higher purchase price of electric vehicles in three years.

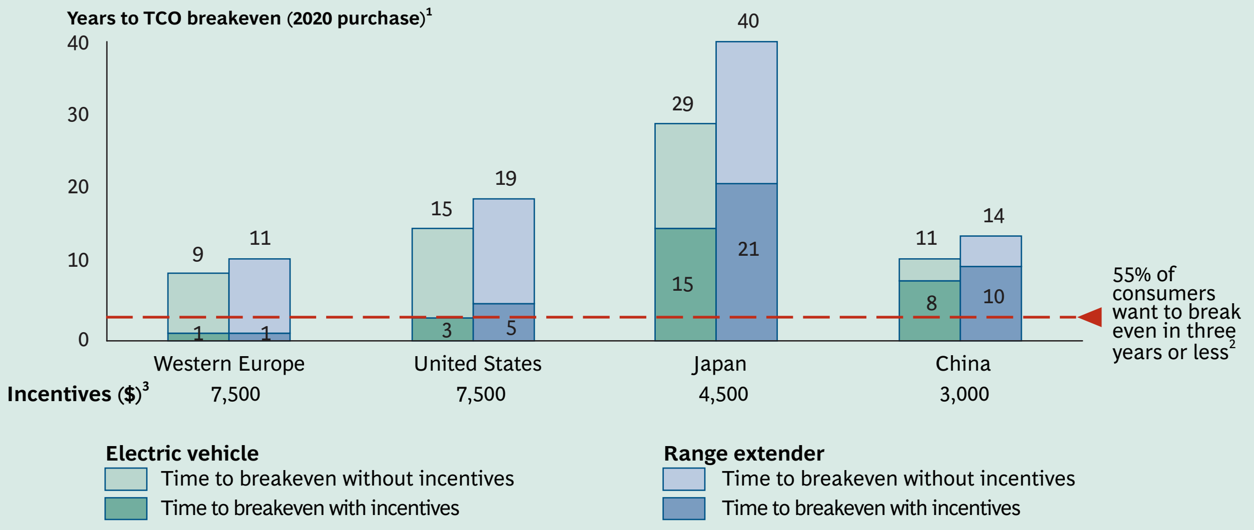
In addition, TCO tradeoffs are a function of operating costs such as the price of fuel, the relative cost of maintenance, and individuals' driving patterns—as well as by government purchase incentives and local tax regimes. If government purchase incentives continue into 2020, they will directly influence TCO tradeoffs at that time. However, current and planned government incentives have been defined as temporary measures and therefore should not be included in a true steady-state calculation of future TCO.

The TCO for electric vehicles is most favorable in regions where gas prices are high relative to the prices of both oil (because of local taxes) and electricity, and where potential owners drive relatively long distances each year. For example, potential owners of a midsize vehicle in the European Union, where gasoline prices are high (because of taxation) and where annual mileage is moderately high, are more likely to find an electric power train economical than drivers in other markets, such as Japan, where people typically drive less and electricity is relatively expensive. The TCO tradeoff in the U.S. market lies in between that of Europe and that of Japan; while the relatively low cost of gasoline makes ICE alternatives more appealing in the United States than elsewhere, U.S. consumers drive more miles per year (approximately 14,000) than drivers in other major markets, expediting the payback on an electric vehicle.

Most countries have adopted incentive programs to stimulate demand for electric vehicles. These programs currently have limited funds; they range from approximately $3,000 per car purchased in China to approximately $7,500 per car purchased in France, Germany, the United Kingdom, and the United States. Certain Japanese programs offer up to $10,000 in electric-vehicle incentives. If these incentive programs continue to 2020, the TCO breakeven period for an electric vehicle—relative to an ICE-based vehicle—in Western nations will fall from 9 to 15 years to 1 to 5 years. (See Exhibit 5.)

Given expected battery economics and technologies, the U.S. TCO breakeven profile will depend on oil and gas prices and government incentives. A number of market surveys suggest that purchasers want to break even on the higher purchase price of electric vehicles in three years through these vehicles' lower operating costs. According to our analysis, in order for U.S. purchasers of electric cars in 2020 to break even in three years, the market would

Exhibit 5. With Incentives, Purchasers of Electric Cars in Western Markets Could Break Even in One to Five Years



Source: BCG analysis.
Note: Breakeven calculations based on the following assumptions for 2020: oil = $100 per barrel; ICE-based vehicle with mileage of 40 mpg; electric vehicle with a 20-kWh battery; and a battery range of 100 miles per 24 kWh.
[1]Reflects the net-purchase-price and operating-cost differences between an electric and an ICE-based vehicle, including taxes.
[2]Continental Corp., Hybrid and Electric Vehicle Survey, 2008.
[3]Incentives assume the extension of 2009 announced benchmarks.

have to meet either one of the following three hypothetical conditions in full or some combination of them to a lesser degree: an oil price increase from $100 per barrel (the forecast price) to $300 per barrel; a 200 percent increase in gasoline prices caused by higher oil prices, higher taxes, or both; or $7,500 in government incentives available per car purchased, consistent with currently approved electric-vehicle incentives.

While it is unlikely that any one of these factors alone will allow purchasers to break even in three years, it is possible that some combination of these and related factors might contribute to such a breakeven period. For example, measures such as carbon taxes and congestion charges are already in force in European markets; it is not unrealistic to think that they might be adopted in the United States, thus reducing the need for sustained incentives.

The Outlook for Industry Dynamics

Competition for share in the estimated $25 billion market for electric-car batteries in 2020 is already under way all along the industry value chain. Rivalry is particularly keen in the area of cell manufacturing, reflecting the critical importance of cells to overall battery performance. In the medium to long term, cell producers will play a crucial role in defining the balance of power—and the way revenues are shared. The key question is, with whom will cell producers join forces?

Two Scenarios for Teaming in the Industry. We envision two possible scenarios for significant strategic alliances in the industry: one in which OEMs forge new alliances with cell manufacturers, and one in which they stick with tradition by buying batteries from tier one suppliers that, in turn, may forge their own alliances with cell manufacturers. (See Exhibit 6.)

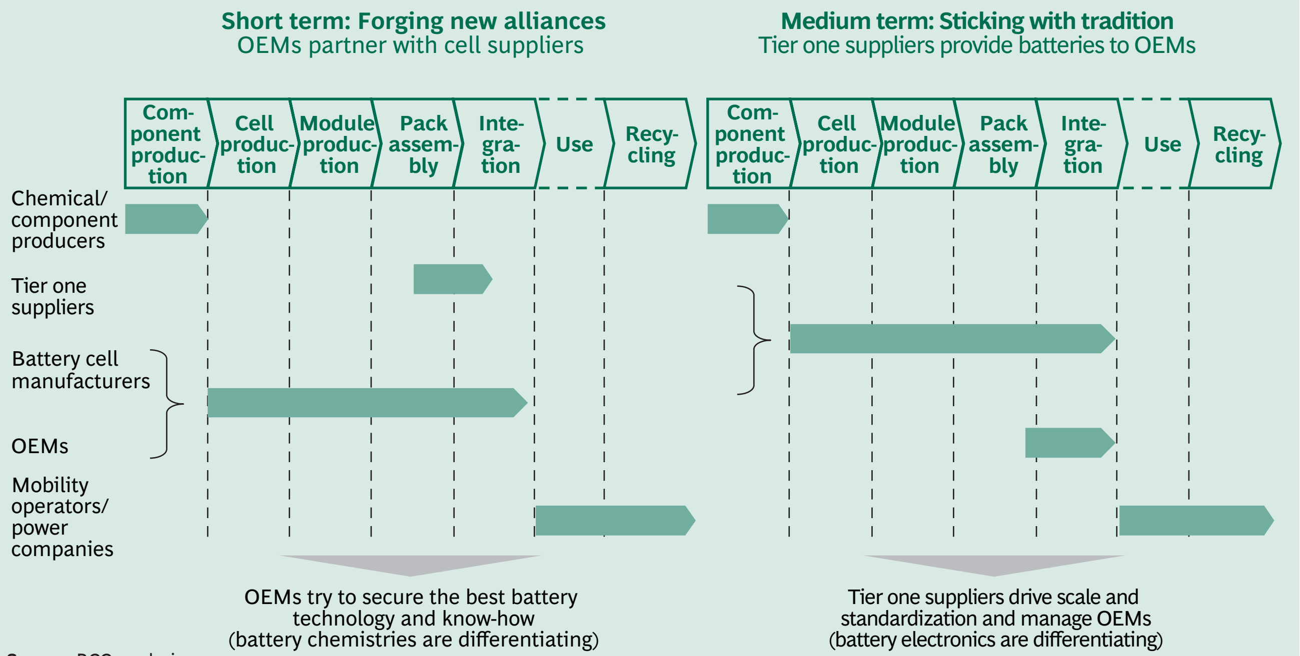
Forging New Alliances. Some OEMs have already established strong links with cell manufacturers through alliances or ownership stakes. Examples are Toyota with Panasonic in Japan and Daimler with Li-Tec in Germany. Such relationships give the OEM exclusive access to the know-how, technology, and production capacity of the cell manufacturer and allow the OEM to differentiate its vehicles in terms of a chosen battery technology. However, relationships of this kind can limit an OEM's ability to react quickly to technological advances achieved by other cell manufacturers. Furthermore, exclusivity can limit scale effects and delay manufacturing-based cost reductions.

Sticking with Tradition. Some tier one suppliers, too, are teaming directly with cell manufacturers. Examples include Johnson Controls' agreement with Saft in the United States and Europe, and SB LiMotive, a joint venture between Samsung (South Korea) and Bosch (Germany). Relationships of this kind allow tier one suppliers to apply automotive-integration expertise to the battery business and give cell manufacturers access to an array of OEMs through established relationships. For OEMs, this model yields less control and less detailed knowledge of battery technology, but it allows them to benefit from the scale effects of leveraging a cross-OEM supply base. It also reduces their up-front costs and the potential cost of switching to an alternative technology, should one emerge. This scenario will be of greatest benefit to OEMs if pack-level standards emerge that allow for flexibility in battery technology.

The Outlook to 2020. A key question that will determine the industry's evolution according to either or both of the scenarios outlined above is how OEMs will trade off control over differentiating technology against scale and flexibility in the short to medium term. In the short term, we expect alliances between OEMs and cell manufacturers to dominate as OEMs continue to learn about the underlying technology and seek to secure an early competitive advantage by quickly bringing exclusive solutions to market. As the technology matures and batteries gradually become commodities, however, margins will fall and scale will become increasingly important, shifting the emphasis to more traditional relationships among cell manufacturers, tier one suppliers, and OEMs.

Implications and Questions for Industry Participants. In addition to OEMs, battery-cell manufacturers, and tier one suppliers, the electric-car battery business includes players that are new to the automotive industry. At one end of the value chain are chemical companies and battery component producers; at the other end are mobility operators, such as Zipcar, and power companies. All are facing stiff challenges as they work to define and secure solid positions on the value chain, and all will be affected by the degree to which governments take action to stimulate investment and demand.

Exhibit 6. Alliances Are Likely to Shift as Cells Commoditize



Source: BCG analysis.

OEMs face an urgent decision in light of the current financial crisis and severely limited resources: how to allocate their investments in new technologies. To answer this question, OEMs must quickly develop battery know-how. We see this happening primarily through partnerships with cell manufacturers, tier one suppliers, and power companies. As OEMs learn, they are also hedging to avoid being locked in with technologically or financially disadvantaged suppliers. OEMs must consider these questions: What is the appropriate tradeoff between learning and risk management? Will this tradeoff change as battery technologies mature and, if so, what leading indicators might exist? How will one electric vehicle be differentiated from others as the technology matures? What are the appropriate investment goals and horizons, and are those of our company in line with others in the industry? How much partnering with other OEMs will provide adequate risk sharing? What do we need from others along the value chain for our business case to succeed?

Cell manufacturers face both great pressure and tremendous opportunity. Product diversity is likely to give way to a technological and cost shakeout in the short to medium term, as players with superior technology win contracts and increase production volumes to decrease prices. We expect these winners to either overcome or acquire smaller players, driving industry consolidation. Cell manufacturers must consider the following questions: What differentiates our technology for the OEM and the customer? How will we remain cost competitive as the industry matures? Are there competitive technologies that are complementary to ours and, if so, how might we integrate them? What assumptions about market size should drive investments?

Tier one suppliers are working to retain their role as an integrator for OEMs as the industry's priorities and cost centers shift toward batteries. They should consider these questions: How do we best become experts in battery technology? What value can we bring to OEMs? How might we drive scale as the industry grows? Do we hold core competencies that the electric-vehicle supply chain can leverage?

OEMs must quickly develop battery know-how through partnerships with other industry stakeholders.

Chemical companies and component producers tend to see the electric-car business as representing only a small percentage of their overall revenues. They will ultimately supply active materials, separators, and other key parts for cell manufacturing, and will likely prefer to use cell manufacturers as intermediaries in order to protect their margins from scrutiny by OEMs and tier one suppliers. These players should consider the following questions: How much investment in new electric-vehicle-specific components is appropriate? Is partnering with a single cell manufacturer or selling products on the open market the better avenue to maximizing profits? What should be our commercialization strategy for new electric-vehicle materials and components?

Mobility operators and power companies are defining new business models based on car usage rather than car ownership. They may play a role in the market penetration of electric cars by reducing customers' up-front costs or by offering solutions to the limitations of electric vehicles, such as their limited driving range and long recharge time. These players must consider the following questions: Does the utility provider business case strengthen or degrade as battery technology improves and costs decline? How robust are the various options for potential battery reuse? Are there certain locations or vehicle segments where a reuse model will be especially appealing? Is the business model most appealing for the organization operating alone or in a partnership?

Governments have begun to assume responsibility for ensuring that companies master battery and electric-car technology and produce large enough volumes to bring costs down. These two steps are essential to the long-term viability of the industry—which, in turn, is one of the key paths to reduced dependence on oil. Given the strong tailwinds of public and corporate interest, we expect that there will be sufficient governmental support to allow the industry to reach both technological maturity and cost viability. In our view, reaching these two industry milestones will correlate with electric vehicles and range extenders attaining a 3 to 5 percent share of the passenger car market in developed countries.

The continued growth of the market for electric vehicles will depend on new battery technologies and the will of governments, as well as on driving patterns and macroeconomic factors, such as the price of gasoline. Regulators may decide to allow pure economics (and environmental needs) to drive the market, thus limiting electric cars' share. Or they may continue to support further market development, implementing sustained tax subsidies and stricter regulation to transfer the cost of the technology to the consumer. Decisions in this arena will have a significant influence on the market's development beyond 2020, notably on the amount of financial support required.

Governments should consider the following questions: What are our investment goals and horizons? Should we bet on specific technologies or portions of the value chain? How and when can we best deploy consumer incentives to drive demand? How should we trade off the consumer economics of electric-vehicle credits with taxes on ICE-based vehicles?

The electric-vehicle and lithium-ion battery businesses hold the promise of large potential profit pools for both incumbents and new players; however, investing in these technologies entails substantial risks. It is unclear whether incumbent OEMs and battery manufacturers or new entrants will emerge as winners as the industry matures. As it stands today, the stage is set for a shakeout among the various battery chemistries, power-train technologies, business models, and even regions. OEMs, suppliers, power companies, and governments will need to work together to establish the right conditions for a large, viable electric-vehicle market to emerge. The stakes are very high.

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Acknowledgments

The authors would like to acknowledge the substantive contributions of their colleagues on the project team: Clemens Hiraoka, Munehiro Hosonuma, Jonathan Nipper, and Annika Weckerle. They would also like to thank Kathleen Lancaster for her help in writing this report and Gary Callahan, Kim Friedman, and Gina Goldstein for their contributions to its editing, design, and production.

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