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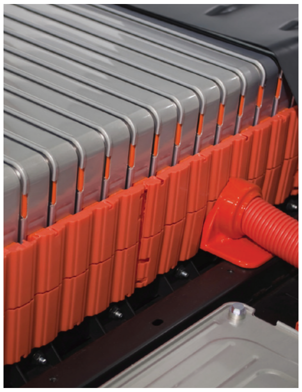


Battery technology charges ahead

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New research suggests that the price of lithium-ion batteries could drop dramatically by 2020, setting the conditions for substantial disruption of several important industries

Most experts agree that energy storage prices[1] will fall in coming years, but there is disagreement about how far and how quickly. Some foresee gradual reductions over decades, while others anticipate dramatic declines over the next 10 to 15 years. It is an important debate because a significant decline in the price of energy storage could have wide-ranging effects across industries and society. In particular, cheaper batteries could enable broader adoption of electrified vehicles,[2] potentially disrupting the transportation, power, and petroleum industries.

To inform the debate, we constructed a bottom-up, "should cost" model[3] that estimates how automotive lithium-ion battery prices could evolve through 2025. The model accounts for likely developments in manufacturing at scale, lower component prices, and capacity-boosting battery technologies that we identified through primary research, expert interviews, and inputs from leading battery-industry players in industry, academia, and government.

Our analyses indicates that the price of a complete automotive lithium-ion battery pack could fall from $500 to $600 per kilowatt-hour today to about $200 per kilowatt-hour by 2020 and about $160 per kilowatt-hour by 2025.[4] In the United States, with gasoline prices at or above $3.50 a gallon, automakers that acquire batteries at prices below $250 per kilowatt-hour could offer electrified vehicles that are competitive, on a total-cost-of-ownership (TCO) basis, with vehicles powered by advanced internal-combustion engines (Exhibit 1).[5]

Of course, adoption of electrified vehicles will depend on a range of factors in addition to battery prices, including macroeconomic and regulatory conditions as well as vehicle performance and reliability. Customer preferences will also be important. Electrified vehicles can offer features such as better acceleration and refinement that attract early adopters, for example, but concerns about range limitations and high up-front costs may lead consumers to "wait and see" before buying.

Moreover, the rate at which different automakers realize lower battery prices could vary by three to five years (the length of a typical vehicle product-development cycle), depending on the investment and power-train strategies they pursue. And the emergence of cheaper batteries is likely to spur innovation in other competing technologies, including internal-combustion engines. This increases the probability that the broader economics of passenger-car transport will be reshaped over the next decade—no matter which technology prevails.

To achieve price reductions of the magnitude outlined above, industry participants will have to increase manufacturing scale, lower component prices, and commercialize capacity-boosting battery technologies now emerging from laboratories. It will not be easy to achieve these objectives, but the consumer-electronics sector is leading the way with rapid advances in consumer lithium-ion batteries. In addition, other sectors, including the semiconductor and solar photovoltaic sectors, have already forged paths that battery players can follow to capture the necessary savings.

If the future unfolds according to our "should cost" scenario, price reductions in energy storage will affect a number of industrial sectors including transportation, power, and petroleum. We conclude this report with several vignettes that explore the implications of our findings for selected sectors.

1 Throughout this document we use the term price (which includes margin) instead of cost, which does not, when discussing energy storage. By price we mean the amount that purchasers of energy storage (for example, automakers) have to pay, inclusive of margins to support reinvestment economics. Exceptions include some instances when "cost" is used as part of a colloquial phrase denoting a concept that includes margins such as "total cost of ownership" and "should cost."

2 At present, vehicles using electricity (electrified vehicles) come in a variety of forms—battery electric vehicles, plug-in hybrid-electric vehicles, and hybrid-electric vehicles—that are increasingly available in today's market.

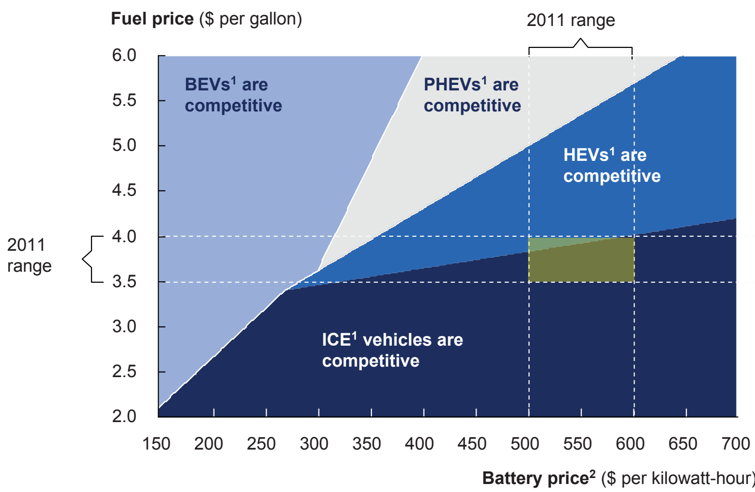
3 "Should cost" modeling is the process of determining what a product should cost in a mature market and considers factors such as raw-material costs, subassembly costs, manufacturing costs, production overhead, and reasonable profit margins. All dollar figures are in 2011 real dollars.

4 These figures represent the price per effective kilowatt-hour, assuming batteries with 70 percent depth of discharge. The price of a battery pack includes the price of battery cells, battery-management systems, and packaging.

5 Our findings are based on results from a five-year total-cost-of-ownership model that considers the prices of advanced internal-combustion-engine vehicles (that is, vehicles that satisfy future US government fuel-economy standards) and electrified vehicles that use 150 watt-hours of electricity per kilometer traveled.

Exhibit 1 Changes in fuel and energy-storage costs and increases in the efficiency of future electrified vehicles could alter the total cost of ownership.

US EXAMPLE



1 BEV = battery electric vehicle; PHEV = plug-in hybrid vehicle; HEV = hybrid vehicle; ICE = internal-combustion engine.
2 Assumes energy usage of 240 watt-hours per mile compared with 305–320 watt-hours per mile today due to, for example, lightweighting, efficient air conditioning; assumes 12,500 vehicle miles travelled per year.

Source: US Energy Information Administration; McKinsey analysis

Building a bottom-up model

We developed a model that disaggregates the price of automotive battery packs into more than 40 underlying drivers—accounting for expected changes in battery manufacturing costs, component prices, and technology—to construct a component-by-component perspective on future battery prices.[6]

The model analyzes inputs from a variety of sources, including detailed interviews conducted with experts in the automotive and battery industries, academia, and government located in North America, Europe, Japan, South Korea, China, and other countries. We conducted:

- Interviews with experts experienced in battery-plant design and manufacturing, who provided insights about future manufacturing costs, as well as interviews with automotive Tier 1 suppliers and battery-assembly companies, which generated insights on overhead costs such as those related to R&D; selling, general, and administrative expenses (SG&A); and warranties

- Interviews with battery-component makers and materials suppliers, which yielded insights about the possible evolution of battery-component prices, and interviews with McKinsey's internal commodity experts, along with an examination of price forecasts by commodities analysts, which shed light on the future prices of raw materials

- Interviews with technical experts from industry, academia, government, and venture-capital firms, which provided insights about how battery technologies are likely to develop

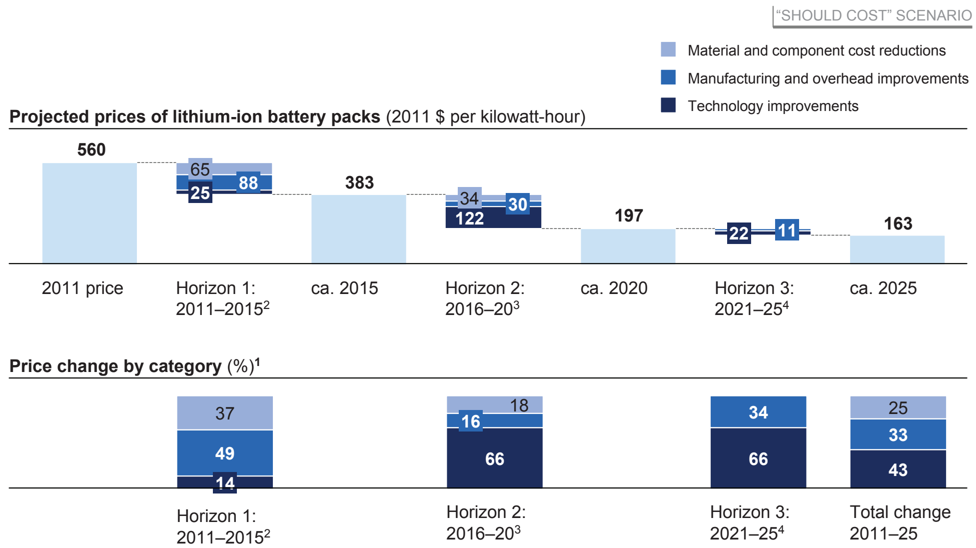
The model's inputs can be adjusted at a granular level of detail, enabling users to generate dynamic insights about the overall effects of advances or setbacks in specific areas. This type of flexibility and sensitivity is critical given that the industry is changing so rapidly, and relatively small developments in discrete areas can significantly affect outcomes.

The path to savings

Our research suggests that three factors could accelerate the day when electrified vehicles become more compelling alternatives, on a TCO basis, than vehicles powered by advanced internal-combustion engines: manufacturing at scale, reductions in battery-component prices, and incorporation of capacity-boosting technologies. Developments in battery manufacturing and component

6 The model builds on work initially done by Argonne National Laboratory, a US government laboratory (cse.anl.gov). We enhanced the model by adding a time dimension, refreshing many of the input assumptions based on our experience and primary research, and factoring in expected cell-capacity changes over time due to material improvements.

Exhibit 2 While the drivers of price improvements are similar in the long run, they have impact at very different points in time.



1 Change from previous horizon (%).
2 Assumes plant scale of 100,000 battery packs per year, cell-capacity increase of 10%, and expected materials cost and margin compression.
3 Assumes continuous manufacturing improvement of 6% for battery-management system and 3% for all other pack elements, cell-capacity increases of 82% from today, and expected materials cost and margin compression.
4 Assumes continuous manufacturing improvement of 6% for battery-management system and 3% for all other pack elements, and cell-capacity increases of 112% from today.

pricing will drive the majority of the savings from 2011 to 2015, while advances in capacity-boosting battery technologies will drive the majority of reductions from 2016 to 2020 and beyond (Exhibit 2).

Manufacturing at scale

Scale effects and manufacturing-productivity improve-ments represent about one-third of the potential price reductions through 2025—a reduction of about $130 per kilowatt-hour on a base of roughly $560 per kilowatt-hour today. Two-thirds of this savings could be captured by 2015.

Most of the opportunity from manufacturing at scale will come from efforts that improve processes, standardize equipment, and spread fixed costs over higher unit volumes. Whereas early automotive lithium-ion battery-assembly plants had the capacity to produce 10,000 to 20,000 battery packs per year from 2007 to 2011, new plants being built today can produce 10 times such volumes—100,000 to 200,000 battery packs per year—at lower per-unit costs. Some of the savings will come from implementing continuous-flow and lean manufacturing techniques that reduce the number of workers needed on the factory floor, saving 60 to 70 percent on per-unit labor costs. Per-unit capital-cost savings will come from optimizing procurement and developing and standardizing high-capacity, high-speed equipment that is purpose-built to produce large volumes of cells. In addition, the ability to spread fixed costs such as R&D and SG&A over higher unit volumes could result in overhead cost declines of 30 to 50 percent.

Yields are also likely to improve as processes become more efficient and manufacturers gain experience. Average battery plants typically achieve yields of 70 to 80 percent today, although experts suggest that today's best-in-class plants achieve yields greater than 90 percent. Based on industry interviews, we expect industry yields to improve to 97 percent by 2020.

Lower component prices

Reductions in material and component prices represent about 25 percent of our projected price reductions—about $100 per kilowatt-hour—all of which is likely to be captured by 2020.

Potential margin compression represents 60 percent of the overall opportunity for component-price reduction. Component makers have EBIT[7] margins of 20 to 40 percent today, but they will come under pressure from battery manufacturers and automakers seeking to drive battery prices down and new entrants in the component segment seeking to gain a foothold by offering lower prices. Margins typical in the specialty-chemicals industry and among best-in-class automotive component suppliers are less than half the level battery component makers currently enjoy. Indeed, the trend toward lower margins is already under way. Increased competition in the cathode market is driving margins down and new manufacturers are entering the separator space at lower price points than those offered by incumbent players.

Potential manufacturing-productivity improvements represent 40 percent of the overall opportunity for component-price reduction. Manufacturers are moving their operations to countries with lower factor costs to realize savings. A copper foil maker from Japan, for example, recently built a new plant in Taiwan to take advantage of lower electricity costs, and companies that manufacture components such as electrolyte salts are building new plants in locations such as South Korea and China to capture savings. Some component manufacturers are decreasing capital costs by building new facilities that combine steps in their production processes, while others are focusing on line balancing to minimize per-unit capital equipment costs.

Note that our analyses make the simplifying assumption that input prices for raw materials such as lithium and cobalt will remain constant through 2025 because experts indicated that increasing demand for these materials is likely to be met with increases in supply. Industry participants should monitor materials prices closely, however, as unexpected increases could have significant effects on battery prices. A sensitivity analysis showed that a 20 percent across-the-board increase in raw-material prices between now and 2020 could increase battery prices by about 8 percent, or $16 (in real dollars), above our 2020 baseline estimate (assuming no substitution of materials).

Capacity-boosting battery technologies

Technical advances in cathodes, anodes, and electrolytes could nearly double battery capacity over the next 10 to 15 years. These opportunities represent 40 to 45 percent of our projected price reductions per kilowatt-hour through 2025, equivalent to about $170 per kilowatt-hour.

New battery cathodes that incorporate what are known as "layered-layered" structures[8] eliminate dead zones that impede ion transfer. The resulting gains in efficiency could improve cell capacity by 40 percent.[9] Experts expect the technology to be commercialized in the later half of this decade.

Silicon anodes currently in development could increase cell capacity by 30 percent compared with the graphite anodes used today,[10] but advances will be needed before they can be commercialized. Current silicon anode designs often swell and crack after relatively few charge and discharge cycles, thus limiting battery life. Manufacturers are developing structures that would allow anodes to swell without cracking. Experts expect silicon anodes to be used first in consumer electronics, but they could be commercially available for electrified vehicles after 2015.

Researchers are also working to identify cathode-electrolyte pairs that can sustain higher voltages and thus boost cell capacity, but the development path is less clear for electrolytes than for other battery materials. Asian manufacturers, particularly in South Korea and Japan, have a strong focus on electrolyte research, and some of our interviewees suggested that advances could enable an increase from 3.6 volts today to as high as 4.8 volts by 2020. Based on the general uncertainty surrounding this area of research, we assume that cell voltages will only rise to 4.2 volts by 2025, which could increase cell-battery capacities by an additional 17 percent compared with 2011. The combination of these three advancements would increase cell capacity by about 112 percent by 2025.

Factors that could impede—or speed—progress

A variety of factors could extend the timeline for price reductions compared with the "should cost" scenario we've outlined, including factors that could alter competitive dynamics in ways that make it more difficult for less expensive components to emerge. Industry participants could be less motivated to accelerate battery development, for example, if future oil prices are lower, future carbon regulations are less stringent, or incentives for owning electrified vehicles are lower than expected. Anticipated efficiencies may not materialize if the industry does not establish standards that enable cooperation across the value chain. And suppliers that develop strong intellectual property may gain sufficient market power to protect their margins, which could slow price reductions.

8 This involves layering of an electronically inactive component with an electronically active component.
9 The Argonne National Laboratory developed a version of this technology and has licensed it to companies such as Germany's BASF and South Korea's LG Chem.
10 Battery prices would not improve in the same proportion as capacity increases because cells that use higher-density silicon anodes would require comparatively more cathode material, which is higher cost than anode material.

Efforts to advance other power-train technologies are likely to intensify as battery prices begin to fall, potentially further reducing the cost threshold for competitiveness among technologies. Innovations will significantly increase the fuel efficiency of vehicles using internal-combustion engines, for example, improving their TCO economics relative to electrified vehicles.

Even if battery prices drop rapidly there is likely to be considerable variation in adoption rates among automakers. Some will wait until their cost targets are in sight before they begin to integrate battery technologies into their platforms. Those that wait put themselves at risk of falling behind, particularly given that product-development cycles are typically three to five years in the industry. But if too many automakers hold out, price declines from scale factors may be slowed, since a portion of the savings depends on increases in sales of electrified vehicles.

Of course, automobiles are not the only catalysts for battery innovation. Customers in the consumer-electronics segment are particularly demanding, and electronics manufacturers are highly motivated to advance battery technologies to ensure that their devices meet customer's design and performance expectations. Thus many advances in battery technologies are likely to be achieved first in consumer-electronics applications—where manufacturing volumes facilitate price reductions—before making their way into the automotive industry.

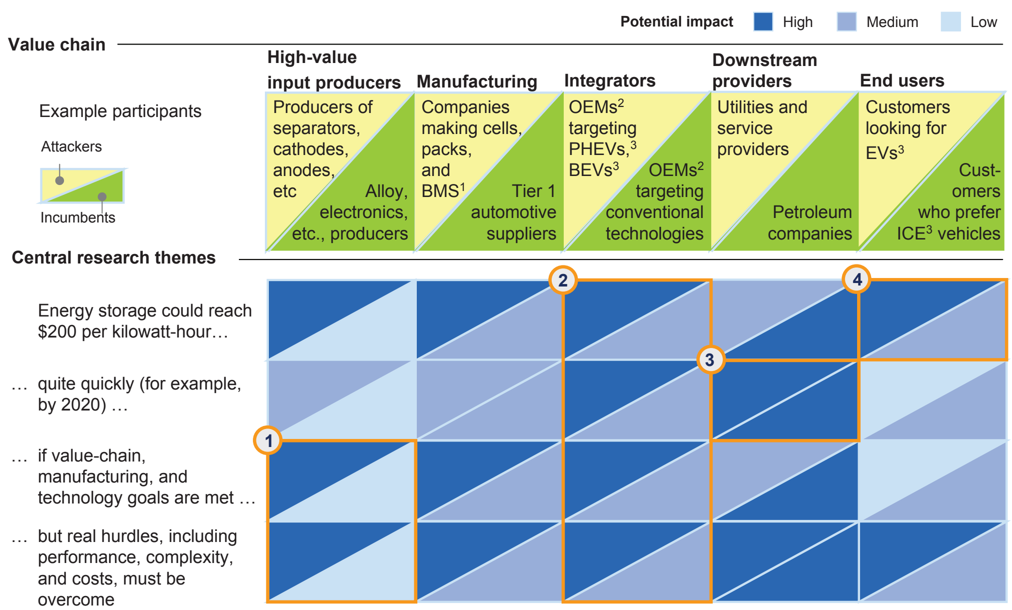
What it means

The emergence of low-cost energy storage could have wide-ranging effects across the energy-storage value chain as it relates to electrified vehicles, posing unique challenges for each segment. Given the range of possible outcomes, there is likely to be vigorous debate among—and within—organizations about how the market will evolve and which strategic directions make the most sense to pursue.

In many cases, groups and individuals will debate the timeline and trajectory for battery-price reductions. They may agree, for example, that battery prices will drop significantly by 2020 but disagree about whether the declines will happen in a linear or accelerating fashion. Or they may disagree about what price declines mean for the industry, particularly if other technologies develop in ways that alter the relative competitiveness of electrified vehicles.

A broad range of value-chain participants—from component and part suppliers to customers—could be affected by developments related to the main themes at the heart of our research: energy storage could reach $200 per kilowatt-hour by 2020 if value-chain, manufacturing, and technology goals are met—but real hurdles to electrified-vehicle adoption, including performance, complexity, and customers' reluctance to pay higher up-front costs, must be overcome (Exhibit 3). And attackers/early adopters will often be affected

Exhibit 3 Participants across the value chain will be affected differently by inexpensive, functional energy storage.



1 BMS = battery-management system.
2 OEM = original equipment manufacturer.
3 PHEV = plug-in hybrid vehicle; BEV = battery electric vehicle; EV = electrified vehicle; ICE = internal-combustion engine.

differently by changes related to these themes compared with incumbents/late adopters.

Below we discuss how entities in four segments of the electrified-vehicle value chain—high-value input, integration, downstream, and end user—might be affected if availability of lower-price batteries leads to wider adoption of electrified vehicles.

1. High-value input producers

Flexibility is an imperative for battery-component makers as technology develops over the next decade. They must understand how component technologies and manufacturing processes are evolving and be able to pivot quickly from their existing focus to embrace emerging innovations that enable price reductions or improvements in quality or performance. Those that are not prepared and able to adapt could be left behind. A number of chemical companies that make battery components are already developing portfolio approaches to diversify their capabilities so they can adapt to rapidly changing conditions (Exhibit 3, circle 1).

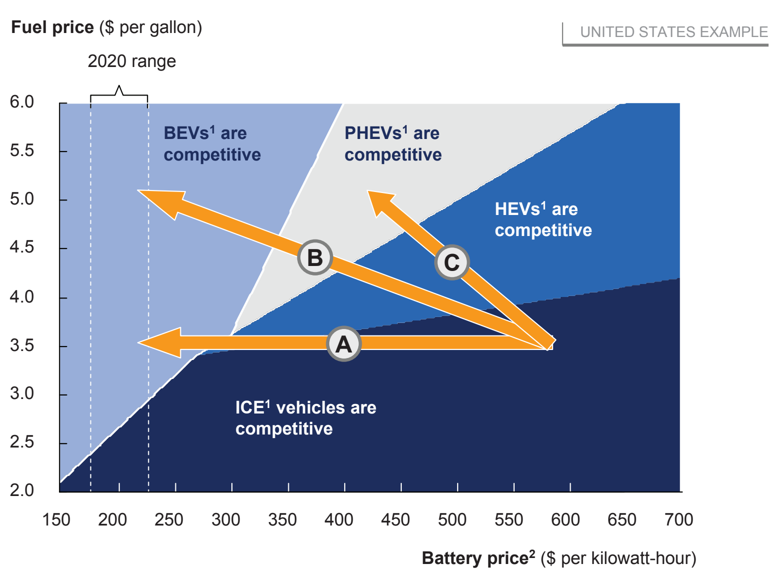
Component makers should also consider developing (or securing access to) small-scale manufacturing capabilities that would allow them to produce complete battery systems themselves. This would allow them to better understand and more fully capture the value that their technology creates. Component makers should also develop strong technical-development and business-development processes that enable them to compare the real-world performance of their products with the performance of competing technologies. This will help them to determine where to focus their product-development investments and when to switch to emerging technologies as the market evolves.

2. Integrators

Even automakers that believe battery prices will fall below $200 per kilowatt-hour by 2020 will have to consider a range of factors to determine which strategic course makes the most sense given their unique circumstances (Exhibit 3, circle 2). They may consider one of the following three strategies in the United States, for example, depending on their beliefs about the speed of battery-price declines and the future price of gasoline:

- **Focus on battery electric vehicles.** This strategy assumes that energy storage prices will decline steadily and gasoline prices will remain roughly constant, between $3.50 and $4.00 per gallon. Thus battery electric vehicles would be competitive sooner under these conditions than under other conditions, potentially reducing the benefit of investing in hybrids (Exhibit 4, circle A).
- **Focus on plug-in hybrids first, then focus on battery electric vehicles.** This strategy assumes that fuel prices will rise and battery prices will decline steadily, leading to a period during which plug-in hybrids

Exhibit 4 Vehicle competitiveness through 2020 depends on the trajectory of reductions in battery prices and macroeconomics.



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2 Assumes energy usage of 240 watt-hours per mile compared with 305–320 watt-hours per mile today due to, for example, lightweighting, efficient air conditioning; assumes 12,500 vehicle miles traveled per year.

Source: US Energy Information Administration; McKinsey analysis are competitive before battery electric vehicles become competitive (Exhibit 4, circle B).

- **Focus on plug-in hybrid vehicles.** This strategy assumes fuel prices will rise but battery prices may fall slowly, potentially opening an extended period during which hybrids and then plug-in hybrids are competitive before battery electric vehicles are competitive (Exhibit 4, circle C).

Advances in energy storage are likely to spur development of competing technologies such as advanced internal-combustion engines, as we have noted, but potentially also hydrogen fuel cells and compressed natural-gas power trains. Automakers should consider the full range of options and develop portfolio strategies that enable them to succeed across segments and regions regardless of which technology dominates. This could be particularly important given that regulatory requirements may evolve significantly in coming years, potentially altering the economics in favor of one type of technology.

3. Downstream providers

The electric power and petroleum industries could be disrupted if penetration of electrified vehicles increases significantly, particularly if penetration increases quickly (Exhibit 3, circle 3). Power utilities could face rapidly changing load curves in areas where adoption of plug-in hybrid or battery electric vehicles spikes. Also, because the power industry depends on the use of long-lived, capital-intensive equipment, owners of traditional power assets (such as gas-fired peak-generation assets) could be put at a significant disadvantage if less expensive options emerge for storing power. Utilities may also face threats from attackers that target their most profitable customers with tailored solutions such as integrated solar packages that provide on-site storage for distributed generation.

Refiners of liquid fuels in developed countries could face disruptions if increasing adoption of electrified vehicles results in lower demand for transport fuels (this may happen due to fuel-economy standards even if electric-vehicle adoption rates remain low). Thus petroleum players should monitor developments closely to ensure they have the time, given their long capital-spending cycles, to adjust their product portfolios before the market shifts.

3. End users

The full potential of low-cost energy storage is probably unknown. Silicon, for example, was first used as an inexpensive alloying agent and then considered as a potential alternative to lead-based pigments in white paint before it was used in transistors and more recently in solar cells. Unanticipated applications for lower-cost energy storage might also have tremendous effects on the automotive or other industries (Exhibit 3, circle 4). Some new applications are already emerging. Studies suggest that electrified vehicles may deliver unexpected benefits to customers in the form of convenience, requiring them to make fewer or no trips to refilling stations; performance, providing them with better vehicle acceleration; and safety, providing them with advanced on-board features such as advanced braking technologies enabled by the availability of high-voltage power. Moreover, electrified vehicles could eventually be used to power other devices at work or at home, or even function as a source of backup power during outages.

Final thoughts

There is still a lot uncertainty surrounding the price progression of lithium-ion batteries. Our research identifies several critical signposts over the next decade that should help provide strategic direction to value-chain participants.

- First, our interviews and analysis suggest that significant price reductions are possible over the next three to five years through the maturation of supply chains and manufacturing processes. Such price reductions depend on the rapidly growing demand for energy storage in consumer-electronics products and on the expansion of electrified-vehicle volumes. By our count, about 75 different plug-in hybrid vehicles and battery electric vehicles could be offered to customers by 2015, providing ample opportunity to assess how consumer demand (and thus price reductions due to scale and learning effects) is unfolding.

- Second, we expect that as new capacity is brought online, significant competition will result in lower margins for many participants, providing another signpost of market evolution.

- Third, in the middle part of this decade, we project that the technical breakthroughs in cathodes and anodes being demonstrated in laboratories will achieve sufficient maturity to be adopted in automotive applications. As noted earlier, we expect the consumer-electronics segment to play an important role as an early technology adopter, providing yet another signpost.

- Fourth, careful attention should be paid to the amount that companies are investing in R&D and the status of emissions regulations. Reduced investments and relaxed regulations would be strong signposts indicating delayed adoption of energy storage.

Our research indicates that batteries could become relatively cheap compared with today's prices, potentially dropping to $200 per kilowatt-hour by 2020. The question is how quickly automakers and others can integrate new lower-price technologies into their operating platforms given typical development cycles of three to five years and product life cycles of five to seven years. Companies dealing with these rapid technology, price, and performance changes will no doubt face many challenges. But bold action could allow market participants to capitalize on one of the biggest disruptions facing the transportation, power, and petroleum sectors over the next decade or more—enabling them to prosper and lead in a landscape that will likely be drastically different from today's.

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