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Electric Mobility: Looking Back to Look Ahead?

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Abstract

This working paper provides an overview of electric cars from their beginnings in the early 20th century to their current entry into the mainstream.

Keywords: mobility; electric vehicle; energy; battery; emissions; environment; car

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"There is every reason to believe that the electric vehicle industry is well established on a sure foundation and that it will grow rapidly, especially in the estimation of the public, without which support no enterprise of a semi-public interest could long exist."

Editorial, *Electrical World*, United States, August 1897[1]

"At that busy corner, Grand Street and the Bowery, there may be seen cars propelled by five different methods of propulsion—by steam, by cable, by underground trolley, by storage battery and by horses."

New York Sun, 1898[2]

"The electric vehicle is destined to occupy a wider field of usefulness in the near future than in the past, due to the improvements constantly being made and the ability of electric cars to travel much longer distances..."

Pope, Studebaker and Baker, Association of Electrical Vehicle Manufacturers, United States, 1906

Historical Perspective

In **1886, Carl Benz** registered the first patent for an automobile driven by an internal combustion engine. In doing so, he gave birth to the automotive industry, "the industry of industries[3]." The Benz car, powered by a small internal combustion engine, had three wheels and can be seen in the Mercedes-Benz Museum in Stuttgart. By 1900, however, Carl Benz's company was joined by almost 500 companies around the world, all of them producing electric cars: the electric motor had become a key form of automotive propulsion and in New York City, for example, it propelled half of the taxi fleet. Most people who could afford a car—generally the upper class—believed that the electric car would be the dominant form of future mobility.

Other elements of an electric mobility ecosystem also emerged. In 1897 the **Electric Vehicle Company** was founded in New York and by 1899 it had become the **largest car manufacturer in the United States**, putting more than 1,000 electric cars on the road. Its owner, Isaac Rice, also acquired the *Electric Carriage and Wagon Company*, which "pioneered a cab system that included service stations for quick change of battery sets, and repair work; vehicles were leased only, not sold" (emphasis added).[4] Under the leadership of William C. Whitney and others, the Electric Vehicle Company "hoped to develop a monopoly by placing electric cabs on the streets of major American cities, starting with New York City, Philadelphia, Chicago, Washington, D.C., and Boston."[5] Around a century later, other companies are trying to achieve the same goal, albeit on a global scale (DiDi, Uber, Lyft, etc.).

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[1] Quoted in David A. Kirsch, *The Electric Vehicle and the Burden of History* (New Brunswick, NJ: Rutgers University Press, 2000), 29.

[2] Quoted in David A. Kirsch, *The Electric Vehicle and the Burden of History* (New Brunswick, NJ: Rutgers University Press, 2000), 11.

[3] Peter F. Drucker, *The Concept of the Corporation* (New York: John Day, 1946), 149.

[4] "Electric Vehicle Company," Wikipedia, last modified September 19, 2019, https://en.wikipedia.org/wiki/Electric_Vehicle_Company.

[5] "Electric Vehicle Company," Wikipedia, last modified September 19, 2019, https://en.wikipedia.org/wiki/Electric_Vehicle_Company.

By 1906 a **battery exchange system** had been developed in Hartford, Connecticut. Customers could buy a car without a battery and pay a flat fee to swap batteries in their cars. In 1910 the Philadelphia and Baltimore area had 27 battery charging stations, feeding a fleet of electric vehicles. New York and Chicago had similar systems. At the same time, the Electric Carriage and Wagon Company was the first to sell mobility services via its electric cabs rather than selling cars.

Today, more than a century later, several of these 19th-century business models are reemerging in a data-driven form: the system of fast **battery swaps** was "reinvented" by *Better Place*, a Silicon Valley start-up founded in 2007. It filed for bankruptcy in 2013, after burning through $850 million of funding.

The idea of selling **mobility services** rather than cars reemerged with Daimler's Car2go and BMW's DriveNow service offerings (among others), enriched by connectivity. The two companies merged their car-sharing divisions in 2019 to create *Share Now*, which had a presence in 26 major cities in 14 countries in North America and Europe as of December 2019. The electric car itself was taken to a new level when Tesla added connectivity, over-the-air updates and data-driven management. In doing so it also brought many concepts from IT to the automotive industry, such as a relentless focus on customer experience, frequent updates, and data collection, to name a few. Tesla thus gave an innovation shock to the industry.

These examples show that many of the ideas emerging today are not completely new but have been taken to a new level by the availability of digital technology. The question is: Will the coming years lead to a similar change in mobility as was seen at the beginning of the 20th century?

Looking back, we see that the initial success of electric vehicles in the late 19th and early 20th century did not last very long. By the beginning of the First World War, most electric cars had disappeared from roads around the world, replaced by gasoline-powered cars.

Several reasons for this can be identified and they allow for some interesting reflections about today's situation. First, when electric vehicles reached a market share of up to 40% of the fleet size in some US cities at the beginning of the 20th century, they were used to travel within urban environments where streets, many of them asphalted, were available. Long-distance travel, such as from New York City to Boston, was still the domain of horse-drawn carriages as roads were in poor condition and recharging stations for electric vehicles were not available. With the discovery of the *Spindletop* oilfield in Texas in 1901 and the start of operations there, the United States was ushered into the oil age and petroleum and its derivatives were available in ample supply.[6] The availability of cheap petroleum generated a wide range of low-cost petroleum-based products, including gasoline and asphalt. The availability of asphalt led to a significant growth of paved streets, including long-distance roads, which in turn enabled cars to make the journey from NYC to Boston. This immediately gave rise to the problem of the limited range of electric cars, due to the limited energy storage capacity of batteries (a problem that still exists today). The problem could not be addressed by battery-exchange models as used in NYC and other cities (the supply logistics could not be resolved) or by charging stations (infrastructure investment and the time required to charge posed problems). More importantly, the Spindletop oil field made cheap oil available in large quantities. Companies such as Gulf and Texaco emerged, with the goal of refining oil into gasoline and its related products. Bertha Benz, the wife of Carl, had to get her gasoline from a pharmacy during the first long-distance car drive in

[6] For a detailed history of the petroleum industry see Daniel Yergin's books *The Prize* (Free Press, 1992) and *The Quest* (Penguin Books, 2011).

1888 but the first gasoline station was established in Saint Louis, Missouri, in 1905, followed by the first drive-in station set up by Gulf Refining in 1913.

On October 7, 1913, Henry Ford's team began experimenting with the moving assembly line. They eventually reduced assembly time by 75%, allowing Ford to drop the price of his cars from $600 to $360, while doubling wages to $5 a day in January 1914.[7, 8] The increasing disposable income of Ford workers allowed many of them to buy the products they were manufacturing, which in turn drove demand for gasoline and led to a growing network of gas stations. While Ford turned the car into a product for the masses, many manufacturers of electric vehicles still used conventional manufacturing processes and this, along with the fact that batteries were expensive, meant their price points were often significantly higher than that of the Model T.

A final blow was given to electric cars in 1912, when Charles Kettering invented the electric starter for gasoline engines. It solved the problem of having to crank the engine manually, a strenuous task that entailed the risk of losing a thumb if handled incorrectly.

The availability of the small internal combustion engine and its electric starter (product innovation), the access to cheap gasoline with its high energy density, the ability to store gasoline in tanks (energy source), a growing network of roads and gas stations (infrastructure) and a superior manufacturing method (process innovation) marked the end of the electric vehicle. These developments were embedded in complex interactions between social and economic structures (e.g., Ford's doubling of wages to $5 a day, which grew the middle class and generated demand), which continue to shape the emergence of large-scale, technology-based ecosystems (of which the automotive industry is one of the largest).

The Return of the Electric Car

Since the advent of the 21st century, interest in electric vehicles has increased substantially. Several reasons can be identified:

Environment: Transportation has led to a significant increase in greenhouse gases (GHG: about 70% of which is CO_2) and particles, contributing to worse air quality especially in urban settings.[9] Governments are therefore implementing regulations to reduce these emissions. For countries such as China it seems to be the only viable alternative to ensure quality of urban life and mobility for a growing middle class. Many politicians and the broader public believe that the electric power train is the best approach to achieve these GHG objectives.

Performance: The properties of the electric power train (immediate torque and small build size) allow for impressive performance, especially in acceleration and longevity. The ability to regain some of the kinetic energy under braking to recharge batteries makes electric cars even more interesting from an environmental perspective. The small build size of electric motors gives designers more freedom to develop new body shapes and make efficient use of the car's footprint.

[7] "100 Years of the Moving Assembly Line," Ford, 2018, http://corporate.ford.com/innovation/100-years-moving-assembly-line.html.

[8] Matt Anderson, "Ford's Five-Dollar Day," The Henry Ford, January 3, 2014, https://www.thehenryford.org/explore/blog/fords-five-dollar-day/.

[9] It should be noted that, on a continental scale, car-related emissions are much lower than many people might expect: for example, less than 10% of CO_2 for Western Europe.

Supply chain: Electric motors have far fewer parts than internal combustion engines (ICEs), so they are easier to manufacture. In an interview with the German publication *Automobilwoche*, Herbert Diess, a board member of the VW Group, estimated that electric vehicles (EVs) will "only have 10% of the complexity of our conventional ICE vehicles."[10] This has two important implications. First, the barriers of entry to the industry are coming down, as less capital (tangible and intangible) is required. New entrants therefore find it easier to enter the industry. Tesla is an example of this: while the company was struggling with "production hell" in 2018 and overall profitability in 2019, its production of about 350,000 cars in 2018 was an impressive achievement and something that would have been rather difficult with traditional cars. Second, many of the established suppliers will have to rethink their business models. For example, electric cars do not need complex gearboxes to act as an intermediary between the revolutions per minute produced by the engine and the wheels on the road. Instead, the electric motor can do the job directly. Similar concerns apply to companies that manufacture exhaust systems, oil pumps, and turbo chargers—that is, all the companies involved in the ICE power train. By 2019, some of the big suppliers (such as Bosch and Continental) had started to downsize parts of the operations that operated exclusively for the combustion engine segment.

Business models: The electric power train significantly increases the digitization level of the car. For example, many EVs use software to manage the individual batteries in their battery packs by means of cell balancing, ensuring that the batteries operate within a defined performance envelope. This helps extend the battery life and reduces the risks of self-induced combustion or other incidents. It is a logical step for original equipment manufacturers (OEMs) to then increase the connectivity of their cars, both to collect data about the cars (especially their batteries) and also to offer new services. This has given rise to product-as-a-service business models, such as car and ride sharing. Driven by the digitization of cars (ICE and electric vehicles alike), the industry as a whole is undergoing significant change and many of the current CEOs have admitted openly that they find it difficult to predict what the industry will look like in 2030. This transformation process will be accelerated with the entry of Industry 4.0 on the factory floor and in the supply chain. The incumbents face many challenges, while greenfield new entrants identify many opportunities by rethinking product, process and business models. China is a showcase for an economy that has embraced the opportunity of electric vehicles. BYD, a major player in battery production, is also one of the largest global manufacturers of electric vehicles. It is but one example of several dozen Chinese companies that develop electric vehicles in an environment created by the Chinese government, which provides support to Chinese companies while putting significant hurdles in the way of foreign OEMs. China sees the automotive industry—including its new dimensions, ranging from connectivity to artificial intelligence—as a strategic industry and the electric car as an opportunity to leapfrog established players in the West. As of 2019, however, the Chinese government was following its plan from 2015 to reduce the subsidies given to Chinese companies that wanted to develop EVs. After a boom phase, it wanted to see which companies had developed a sustainable business model. Some of the former star companies, such as NIO, however, were facing significant challenges.

Market: Millennials and younger generations attach more value to their smartphone than to owning a car. This change in perception has made the auto industry's traditional marketing tools (e.g., a focus on performance and quality) less effective. Furthermore, as more and more people live in urban areas, the daily experience of traffic congestion does not help to make the privately owned car an interesting value proposition. Instead, mobility services in the form of car and ride sharing offered by companies such as Share Now and DiDi are more attractive to the younger

[10] Henning Krogh, "VW-Markenchef Diess im Interview: „Wir haben eine lange Strecke vor uns“," *Automobilwoche*, no. 24 (November 2017).

generations. The growth rate of these services is significant, reflected by the valuation of such players as DiDi and Uber. This growth can be attributed to the reluctance to own such a costly asset as a car but also to the superior customer experience provided by mobility services. Car sharing represents a significant challenge to established OEMs as they make most of their profits from large cars while A- and B-segment cars (e.g., the VW Up and VW Polo)—which are perfectly suited to the requirements of urban mobility—provide smaller profits.

With the adoption of electric vehicles, driven by the factors outlined above, traditional car makers are under significant pressure to innovate their business models, processes and products.

Challenges for the Electric Car

While the public opinion has turned to the electric car as a smart solution for mobility and to reduce emissions, several questions need to be addressed and clarified before its widespread use would make sense. These include the following:

Battery cost: One of the key elements of any electric car is the battery, particularly the lithium-ion (Li-ion) cells (currently the most widely used technology for battery electric vehicles or BEVs). Cars require more sophisticated batteries than smartphones. Car batteries need to meet stringent targets for cost, rated kilowatt-hour (kWh) capacity, specific energy, specific power, peak power, state of charge, depth of discharge, cycle life, and battery reversal, crash safety (to name a few).[11] Compared to smartphones, cars have to operate in a far broader temperature range, are used for much longer (about 10 years in Europe) and have to fulfill more complex safety requirements (e.g., crash tests). This makes battery packs for cars more difficult to manufacture and more expensive. A report published in 2010 estimated the cost of installed battery packs at around $1,000 per kWh. The report predicted that, by 2020, costs would drop by more than 60% to around $400 per kWh.[12] In 2015, Nykvist and Nilsson collected public data on battery costs for electric cars and put the average cost at $400 per kWh that year (with outliers ranging from $250 to $500). The authors estimated an average cost of $300 per kWh for Tesla (without power electronics and a battery management system). This put the cost of the battery pack of a Tesla Model S P85D (the most powerful model available in 2014) at a minimum of $25,500, which was the manufacturer's suggested retail price (MSRP) of a brand new Ford F-150 pickup, the best-selling vehicle in North America. The authors stated:

> We reveal that the costs of Li-ion battery packs continue to decline and that the costs among market leaders are much lower than previously reported.
>
> … it is indeed possible that economies of scale will continue to push the costs towards US$200 per kilowatt in the near future even without further cell chemistry improvements. However, these cost reductions depend on the successful implementation of these large scale battery production facilities and on continued public support through, for example, economic incentive schemes in key BEV markets.[13]

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[11] For more details see Kwo Young, Caisheng Wang, Le Yi Wang, and Kai Strunz, "Electric Vehicle Battery Technologies," in *Electric Vehicle Integration Into Modern Power Networks*, ed. Rodrigo Garcia-Valle and João A. Peças Lopes (New York: Springer, 2013), 15–56.

[12] Boston Consulting Group (BCG), "Batteries for Electric Cars," 2010, https://www.bcg.com/documents/file36615.pdf.

[13] Björn Nykvist and Måns Nilsson, "Rapidly Falling Costs of Battery Packs for Electric Vehicles," *Nature Climate Change* 5 (2015): 329–32.

Figure 1
Li-Ion Battery Costs: 2015 Versus 2017

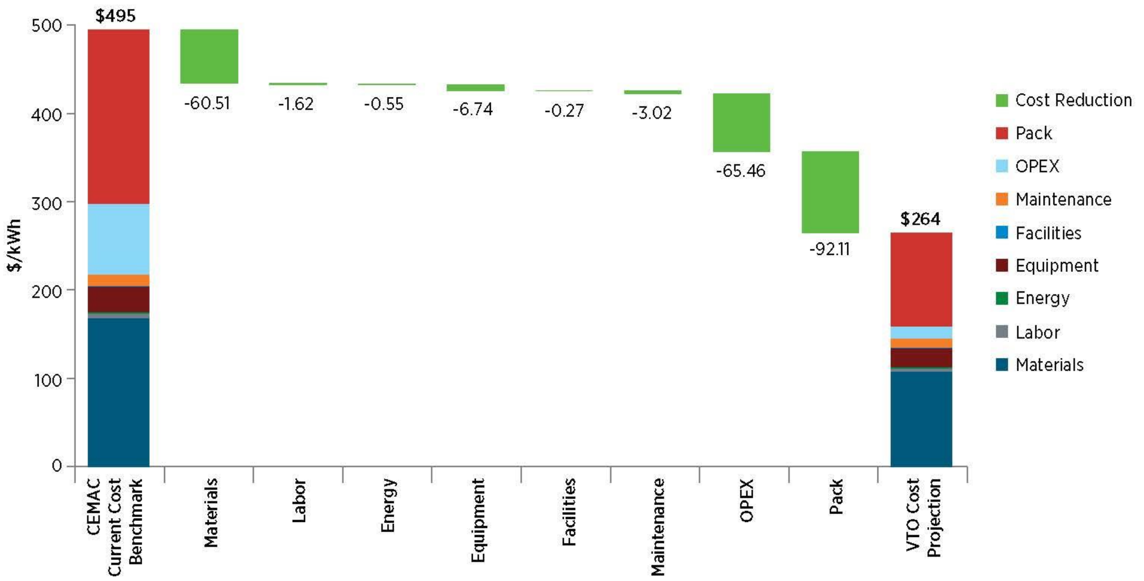

Figure 3. Comparison of 2015 modeled cost of commercially available technology (CEMAC) and current modeled cost projection for innovative technologies in development (VTO). Illustrative cost reductions are driven by potential improvements in energy density and manufacturing yield.

Source: US Department of Energy, *Cost and Price Metrics for Automotive Lithium-Ion Batteries*, February 2017, 3, https://www.energy.gov/sites/prod/files/2017/02/f34/67089%20EERE%20LIB%20cost%20vs%20price%20metrics%20r9.pdf.

A report published in February 2017 by the US Department of Energy (DOE) estimated that costs could fall to about $200 per kWh by 2020 in a best-case scenario of technological advance and high-volume production.[14] Several reports have estimated that, sometime between 2022 and 2026, battery costs will drop to the critical threshold of $150, implying cost parity between electric and ICE vehicles. For 2017, the DOE report still put the cost at more than $200 per kWh.[15] (See **Figure 1**.) In a 2019 report, Ding et al. stated: "To enable EVs that are cost-competitive with ICEVs [ICE-powered vehicles], the costs of battery packs need to fall below $125 kWh^{-1}, which is also a target set by the US DOE for 2022."[16] In this context, the raw materials used to produce batteries play a crucial role. The automotive industry finds itself exposed to a fierce and very large competitor for raw materials: the consumer electronics industry. Both industries need access to the same minerals and rare earth elements, giving rise to significant price swings and occasional shortages. For example, the price of cobalt, a key material used in the production of batteries, increased threefold between 2016 and 2018. Astute investors may see a unique opportunity to play the markets, benefiting from temporary supply shortages. Furthermore, mineral deposits of several key ingredients of Li-ion batteries can be found in politically unstable

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[14] US Department of Energy, "Cost and Price Metric for Automotive Lithium-Ion Batteries," February 2017, 3, https://www.energy.gov/sites/prod/files/2017/02/f34/67089%20EERE%20LIB%20cost%20vs%20price%20metrics%20r9.pdf.

[15] See also Bloomberg New Energy Finance, *Global EV Trends*, 2017.

[16] Yuanli Ding, Zachary P. Cano, Aiping Yu, Jun Lu, and Zhongwei Chen, "Automotive Li-Ion Batteries: Current Status and Future Perspectives," *Electrochemical Energy Reviews* 2 (2019): 1–28.

regions in Africa (e.g., in 2017 some 60% of the world production of cobalt came from the Democratic Republic of the Congo) or in nations with a geostrategic agenda (e.g., China, which as of 2016 had acquired seven of the 10 largest Congolese producers of cobalt).[17]

Financial and fiscal considerations: Comparisons of the total cost of ownership (TCO) for traditional cars and EVs often ignore the fact that taxes paid for hydrocarbons at the pump put traditional cars at a disadvantage. In Europe, an average of 63% of the price paid at the pump is taxes. With increasing numbers of motorists moving to EVs, governments of populous European countries such as France and Germany would have to find ways to compensate for this lost income stream. In many European countries, the tax levied on hydrocarbons used for cars is up to seven times higher than the tax levied on hydrocarbons used for energy generation. If the same rate of taxation were applied to electricity, this would make the business case for EVs more complicated than it is already.

Energy mix: In the discussion of the advantages of electric mobility, often comparisons are made between the current ICE system and the EV system without ensuring comparable system boundaries. A typical example of this is the focus on tailpipe emissions: everybody can see that, unlike traditional cars, EVs generate no tailpipe emissions. So, obviously, the electric car must be better. Some doubts arise, however, as the tailpipe focus fails to include the source of energy for the EV—that is, the generation of electricity. Several studies have analyzed the effect of EVs by including energy generation within the system boundaries. A study by Holland et al. (2015)[18] may serve as an example. The authors find that, given the energy footprint in the United States, EVs should be taxed(!) at up to $5,000 at the time of purchase in the East Coast and Midwest states, where electricity generation is primarily carbon-based. On the West Coast, where renewable energy represents a significant percentage of the energy mix (e.g., hydropower from the Columbia river system), the authors find that subsidies of up to $5,000 would make sense. This example illustrates that system boundaries have a sizable effect on the environmental performance of battery electric or ICE vehicles.[19] It also makes a strong case for improving the energy mix in Europe and North America. The results of Holland et al. (2015) show that, with the wrong energy mix, electric vehicles shift carbon dioxide (CO_2) and nitrogen oxide (NO_x) emissions from inner cities to rural areas, where power generation plants are located. Similar insights apply to China, where the energy mix is unsuitable for supporting the widespread introduction of EVs, which would increase GHG emissions rather than reduce them. The Chinese government has responded by building multiple nuclear power plants, replacing CO_2 and NO_x with nuclear waste.[20]

Cradle to grave: Discussions of electric mobility increasingly include the topic of the energy mix, as discussed in the previous paragraph. A full assessment of the environmental impact, however, needs to include the emissions generated during the mining of raw materials for battery production (cradle) and end-of-life (grave) considerations—that is, the eventual disposal of

[17] Elisabeth Behrmann, Jack Farchy, and Sam Dodge, "Hype Meets Reality as Electric Car Dreams Run Into Metal Crunch," Bloomberg, January 11, 2018, https://www.bloomberg.com/graphics/2018-cobalt-batteries/.

[18] Stephen P. Holland, Erin T. Mansur, Nicholas Z. Muller, and Andrew J. Yates, "Environmental Benefits From Driving Electric Vehicles?", NBER Working Papers Series 21291, National Bureau of Economic Research, 2015, http://www.nber.org/papers/w21291.pdf.

[19] BEVs are pure electric vehicles, while the category of electric vehicles generally also includes plug-in hybrid EVs (PHEVs). The latter hybrids have both an ICE and an electric motor, and batteries can be recharged by connecting the car to an electricity outlet (hence "plug-in").

[20] At the start of 2020, the Chinese mainland had "about 45 nuclear power reactors in operation, 12 under construction, and more about to start construction." See: "Nuclear Power in China," World Nuclear Association, last modified February 2020, http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx.

spent batteries. Current battery and electric motor technologies require significant amounts of rare earth elements. These elements are not rare as such but their concentration in the earth's crust is very low. As a result, significant volumes of material have to be mined and processed to produce relatively small amounts of these materials, particularly when virgin materials are used. The Argonne National Laboratory in Illinois reviewed scientific literature on this topic.[21] Analyzing the results of several publications on cradle-to-gate[22] emissions, its report's authors found that, during the production of a 1 kilogram Li-ion battery, 12.5 kilograms of CO_2 and 14.5 grams of NO_x were generated on average. (This excludes the usage cycle of the battery—that is, emissions from electricity generation during the use of the battery.) This would translate into close to 10 tons of CO_2 and more than 8 kilograms of NO_x generated during the production of the largest battery pack used in EVs today. By way of comparison, a diesel car that meets stringent Worldwide Harmonized Light Vehicles Test Procedure (WLTP) Euro 6-Temp regulation requirements could drive 50,000 kilometers before reaching the same level of CO_2 emissions or 100,000 kilometers before generating the same level of NO_x emissions. In many comparisons of ICE and battery electric vehicles, these initial emissions are ignored.

At the end of their life cycle, batteries need to be disposed of. This also presents a challenge, given the concentration of metals such as cadmium and other elements. An interim solution is the second life use of batteries: once their capacity has faded to 70% of the original value, the batteries are decommissioned from EVs and used, for example, as fixed electricity storage in domestic or business settings.[23] They can play an important role in smart grid solutions, which in turn help with the introduction of regenerative "green" electricity generation and distribution. For the next few years many of the batteries that are removed from EVs could be absorbed into this market. In many countries, however, the lack of suitable business models and the presence of regulatory hurdles limit the absorption rate. Strong growth of domestic battery packs to store renewable energy would generate challenges in relation to keeping the electricity grid stable and the energy utilities profitable. While the absorption rate of used battery packs into second life usage will increase in the near term, eventually it will reach a steady state and the battery packs will have to be disposed of at a rate similar to the rate of decommissioning—that is, several million cars per year in Europe. China, which has taken a lead in electric mobility, is already facing some of these challenges. It could be facing a volume of 170,000 tons of lithium battery waste in 2018 and this volume will increase steadily with the government-induced adoption of EVs.[24] To put this in perspective: the largest installation for recycling Li-ion batteries in Europe has a capacity of 20,000 tons per year, and Europe overall has an installed capacity of less than 45,000 tons.[25] Similar numbers apply to China, where some recycling companies see no business

[21] John Lorenzo Sullivan and Linda Gaines, *A Review of Battery Life-Cycle Analysis: State of Knowledge and Critical Needs* (Oak Ridge, TN: Argonne National Laboratory, US Department of Energy, 2010), https://greet.es.anl.gov/files/batteries_lca.

[22] Cradle-to-gate: from mining of raw materials to batteries leaving the factory gate.

[23] As the number of loading cycles of a battery pack increases, its capacity to hold energy decreases. This is called "fading." The National Renewable Energy Laboratory in Colorado has found that Li-ion batteries "typically fade in a graceful manner from beginning through the middle of their lifetime" but after that, however, "performance can sometimes rapidly degrade" (Kandler Smith, "Battery-Life Trade-Off Studies," in *IV. Battery Testing, Analysis and Design*, Energy Storage R&D FY 2013 Annual Progress Report, US Department of Energy, 134, https://www.energy.gov/sites/prod/files/2014/05/f15/APR13_Energy_Storage_e_IV_Battery_Tstg_Design_2.pdf).

[24] David Stanway, "China's Recyclers Eye Looming Electric Vehicle Battery Mountain," Reuters, October 23, 2017, https://www.reuters.com/article/us-china-batteries-recycling-insight/chinas-recyclers-eye-looming-electric-vehicle-battery-mountain-idUSKBN1CR0Y8.

[25] A Tesla Model S P100D carries a battery pack of about 800 kilograms, which is the largest battery pack of all passenger EVs. This would translate to a total recycling capacity of 50,000 vehicles compared to annual new car sales in Western Europe of 14.2 million units.

case for Li-ion batteries as recycling costs outweigh potential revenues.[26] In 2016, there was a shortage of appropriate policies and collection systems for batteries in China, despite growing community concern about the impact of waste lithium-ion batteries on the environment and public health.[27] Once the recycling capacity is available, however, reverse logistics becomes a challenge: to ensure an efficient circular economy, the recycling system must achieve a high collection rate of used battery packs—and a high efficiency rate in the recycling process itself. To be economically viable, recycling facilities need to be on an industrial scale, which requires significant investment. Hendrickson et al. (2015) analyzed the supply chain logistics of battery recycling in California and concluded that two recycling facilities would be the best solution to balance economic and environmental constraints.[28] To keep the facilities operating at high utilization levels, there would need to be an industrial-scale inflow of used battery packs. Reverse logistics becomes an interesting problem in this setting and, for the foreseeable future, diesel-powered trucks will have to transport the spent batteries to the recycling facilities.

Efficiency: Another argument often used by proponents of the electric vehicle is the transformation of electric energy into kinetic energy—electric motors easily achieve an efficiency of more than 90%, while the best internal combustion engines used in cars achieve 40% (diesel) or less (gasoline). Focusing on the high efficiency of the electric motor leads to a failure to take account of the transformation of chemical energy into electric energy, a process taking place in the electricity plant. In a 2017 study, Teufel et al.[29] point out that, if the whole energy chain is considered, both forms of propulsion translate only about 30% of primary energy (e.g., hydrocarbons) into kinetic energy. What is worse, the diesel engine fares better than the electric motor. The authors point out, however, that the use of regenerative electricity generation will improve the balance for the electric motor, eventually making it superior.

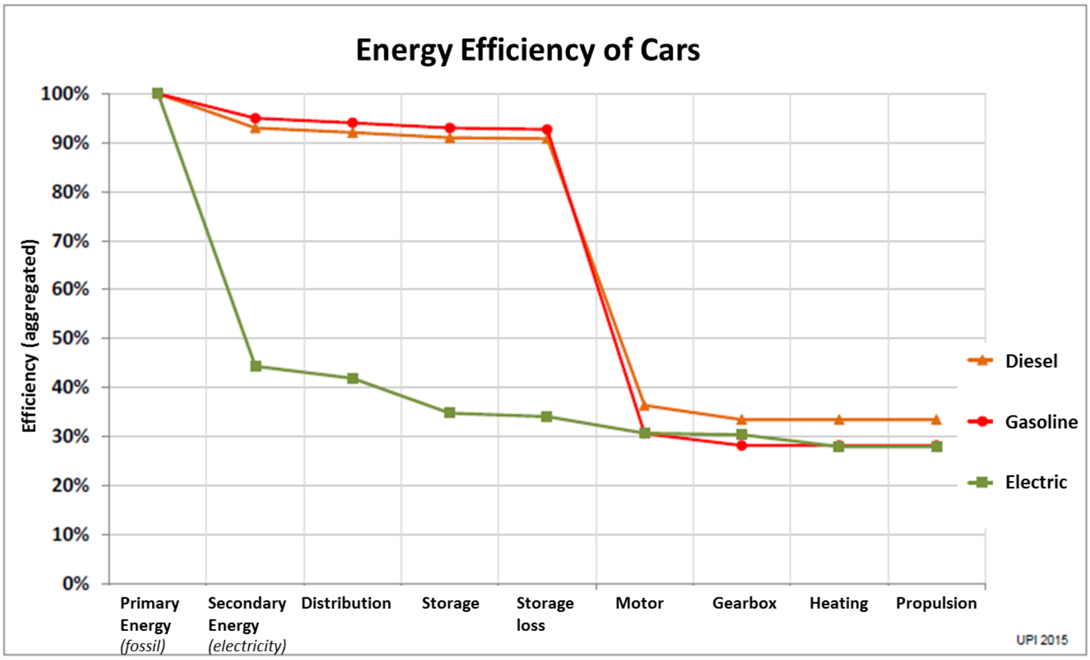
[26] Stanway (2017): "one recycling company [was cited] as saying that the value of materials extracted from one tonne of lithium-iron-phosphate battery waste stood at 8,110 yuan, but the cost of recycling them would be 8,540 yuan."

[27] Stanway (2017).

[28] Thomas P. Hendrickson, Olga Kavvada, Nihar Shah, Roger Sathre, and Corinne D. Scown, "Life-Cycle Implications and Supply Chain Logistics of Electric Vehicle Battery Recycling in California," *Environmental Research Letters* 10, no. 1 (2015).

[29] Dieter Teufel, Sabine Arnold, Petra Bauer, and Thomas Schwarz, *Ökologische Folgen von Elektroautos*, Umwelt- und Prognose Institut (UPI), Bericht Nr. 79 (Report no. 79), 2nd ed., 2017, http://www.upi-institut.de/UPI79_Elektroautos.pdf. The UPI is an independent research institute, based in Heidelberg, Germany.

Figure 2
Energy Efficiency of Cars



Source: "Energieausnutzung PKW," Teufel et al. (2017, 49).

Natural resources: Li-ion batteries for EVs include a broad range of materials, such as lithium (Li), nickel (Ni), cobalt (Co), manganese (Mn), aluminum (Al), copper (Cu), silicon (Si), tin (Sn), titanium (Ti) and carbon (C) in a variety of forms. Of these, cobalt, natural graphite and silicon metal fall into the category of critical raw materials, meaning that they are of great economic importance and there is a high supply risk.[30] With the growth of electric mobility, the supply of cobalt will come under pressure and the European Commission referred to estimates that, by 2050, "the cumulative demand for cobalt would require all the resources known today, even considering its relatively high recycling rate in the battery sector."[31] Recent price movements of cobalt give an indication of this development. In practically all areas that are relevant to the production of batteries for electric vehicles, China plays a leading or important role. The Chinese government moves very strategically: for example, it helps Chinese companies acquire cobalt deposits in the Democratic Republic of the Congo, effectively bans ICE cars from large cities in China, and stringently regulates foreign car manufacturers in China. Furthermore, the tectonic change being experienced by the automotive industry provides a unique opportunity for China to leapfrog established players from Europe, Japan, North America and South Korea.

[30] See the "Critical Raw Materials" list published by the European Commission on a regular basis: http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en.

[31] Natalia Lebedeva, Franco Di Persio, and Lois Boon-Brett, *Lithium Ion Battery Value Chain and Related Opportunities for Europe*, JRC Science for Policy Report (Petten, Netherlands: European Commission, 2016), 9, https://ec.europa.eu/jrc/sites/jrcsh/files/jrc105010_161214_li-ion_battery_value_chain_jrc105010.pdf.

Outlook

The electric car is part of a new ecosystem. It will be able to deliver its full potential only if it is supported by a new charging infrastructure, a clean energy mix, green factories, innovation to reduce the dependence on some critical minerals (such as cobalt), intelligent design to limit the size of the battery, and a circular economy that makes intelligent use of recycled materials. It remains doubtful whether BEVs with large batteries are a way to help the environment, given the problems outlined above. Furthermore, these cars do not help solve another key problem: congestion in urban environments.

A car with the potential to solve all of these challenges would be a small, electric, connected purely urban vehicle. It would be small, because this size would reduce its footprint and thereby help to reduce congestion and parking problems in urban settings. To get similar utility from a small car compared to current mid-size cars, it would be necessary to make efficient use of its small footprint. Using an electric power train would help to achieve this goal: wheel-hub engines would move the motor from body to wheels, while the battery and power electronics could be located in the floor of the car, freeing up a lot of space for passengers and luggage. Making it a purely urban car would eliminate two challenges traditional car makers have to solve. The first is range anxiety—the ability to drive the car for 500 kilometers or more before having to recharge it. A purely urban car would have to cover significantly smaller distances and, given the right infrastructure, it could be charged at many locations across a city. The second typical challenge is that of passenger safety: traditional cars are very expensive to develop, in part because they have to meet a myriad of stringent crash tests at varying speeds. A car designed for urban environments can be limited to a top speed of 80 kilometers per hour, thereby reducing the need for complex safety engineering. This would also reduce its mass, in turn reducing its energy needs. The limit to urban settings would also make the wheel-hub engine a viable alternative, as its disadvantages in terms of handling and drive dynamics would be less of an issue. Making the car connected would allow it to be used in different business model settings (e.g., ownership and shared models) and would be a prerequisite for autonomous driving. Last but not least, a small, electric purely urban vehicle would not need a large battery, thereby reducing some of the negative externalities outlined above.

Several implications can be identified. First, the structure of the value chain will change. Small, connected urban electric vehicles have far lower service requirements than traditional cars. OEMs will be tempted to sell them directly to motorists, bypassing dealerships. Manufacturers will not be able to do so, however, as long as most of their revenue stream is generated by this traditional distribution channel. It may be assumed that a new form of value generation among the different players in the value chain will emerge. In this transition process, dealerships will be under significant pressure to change and stay profitable. Second, OEMs will also be affected. A small, electric, connected purely urban vehicle has a low product complexity and a much simpler supply chain and therefore could be produced more easily and at a significantly lower cost. The growth of younger user segments has the potential to make the car hardware more of a commodity: these segments attach less importance to the car's exterior design but much more to its interior and connectivity as well as customization via apps etc. Differentiation of the car would be primarily via software customization, and less via hardware. This setting could be dangerous for established OEMs because, once the hardware had effectively become a commodity and Industry 4.0 had been introduced, the door would be open to new entrants. If a small, electric, connected purely urban vehicle were to become merely a device like a smartphone and so differentiate itself via customization of its software (e.g., all the sides and ceiling in the interior could be covered with flexible displays that could display anything the passengers wanted), then new players would enter the industry. They would produce several hundred thousand identical purely urban vehicles on fully automated assembly lines, using networked robots and other elements of Industry 4.0. As mentioned, products would be differentiated via software and there would be a stringent focus on the customer experience in the car. The established players will have to move quickly to occupy this space. If not, the story of the iPhone will be repeated and many “Nokias” will see their financials under press