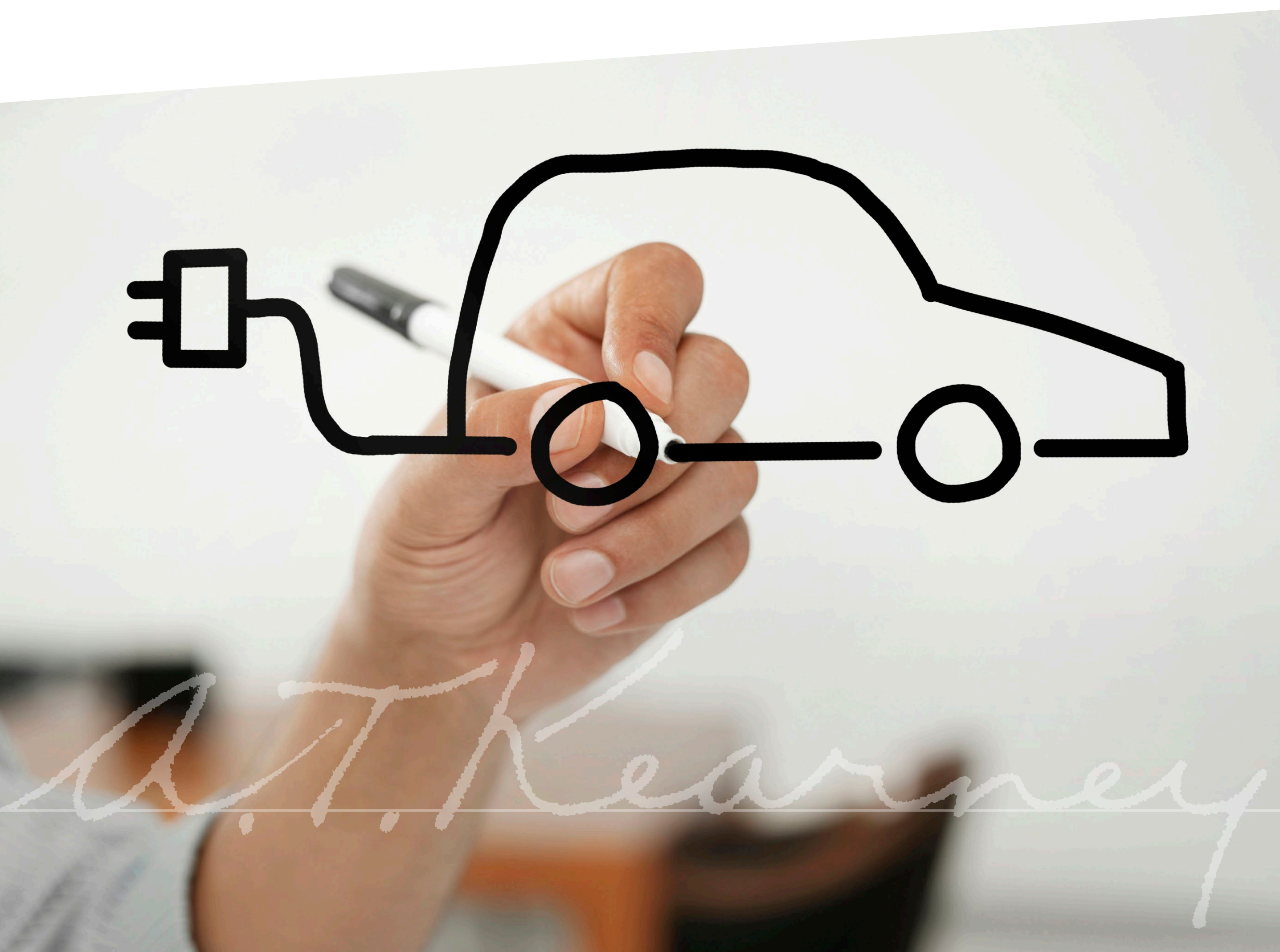
A.T. Kearney | Energy Transition Institute

Natural Resources and CO_2: Hazards Ahead for Battery Electric Vehicles?

With the electric vehicle and battery markets on the brink of explosive growth, governments must proceed with caution as they manage these fast-moving industries.



Foreword

New energy technologies and innovations are disrupting the energy industry as we know it.

The global energy transition is *fast-tracking* electric vehicle production worldwide. The deployment of electric vehicles is a key energy transition mega trend with direct impact on major business transformations not only in the car industry but also across the conventional oil and gas, utilities, and even mining sectors. Many leaders are intensively focused on understanding those changes and elaborating new business models to design our futures economies.

Electric vehicles just exceeded 2 million globally, about 0.2 percent of the more than 1 billion vehicles on highways worldwide. Some say the market is "much ado about nothing," while others forecast explosive growth ahead. What many may not be aware of is that the market is disproportionate across countries and might already deeply impact local markets. In Norway, for example, 30 percent of all new cars sold are electric, making it difficult for refueling station owners to keep up with demand.

Besides direct consequences for the carmakers and refueling stations, it is important to understand the upcoming battery electric vehicle (BEV) revolution. As the white paper mentions, there are underappreciated growth risks: the scarcity of natural resources, the need for effective systems and processes for battery recycling, and the possibility of insufficient CO_2 emissions reductions. We anticipate the need to develop new battery technologies and a substantial battery-recycling industry.

As illustrated by the BEV example, the energy transition brings new technology solutions that will impact most industries. It's important to explore and anticipate the economic implications of those new technologies. The success of the new business models will largely depend on the degree of foresight and investment returns sought.

The role of the A.T. Kearney Energy Transition Institute is to provide leading insights on global trends in energy transition, technologies, and strategic implications for private sector businesses and public sector institutions. I express sincere appreciation to Claude Mandil, Dr. Adnan Shihab-Eldin, Antoine Rostand, Erik Peterson, and Kurt Oswald for their valuable insights and contribution to the Institute.

Richard Forrest
Chairman, A.T. Kearney Energy Transition Institute

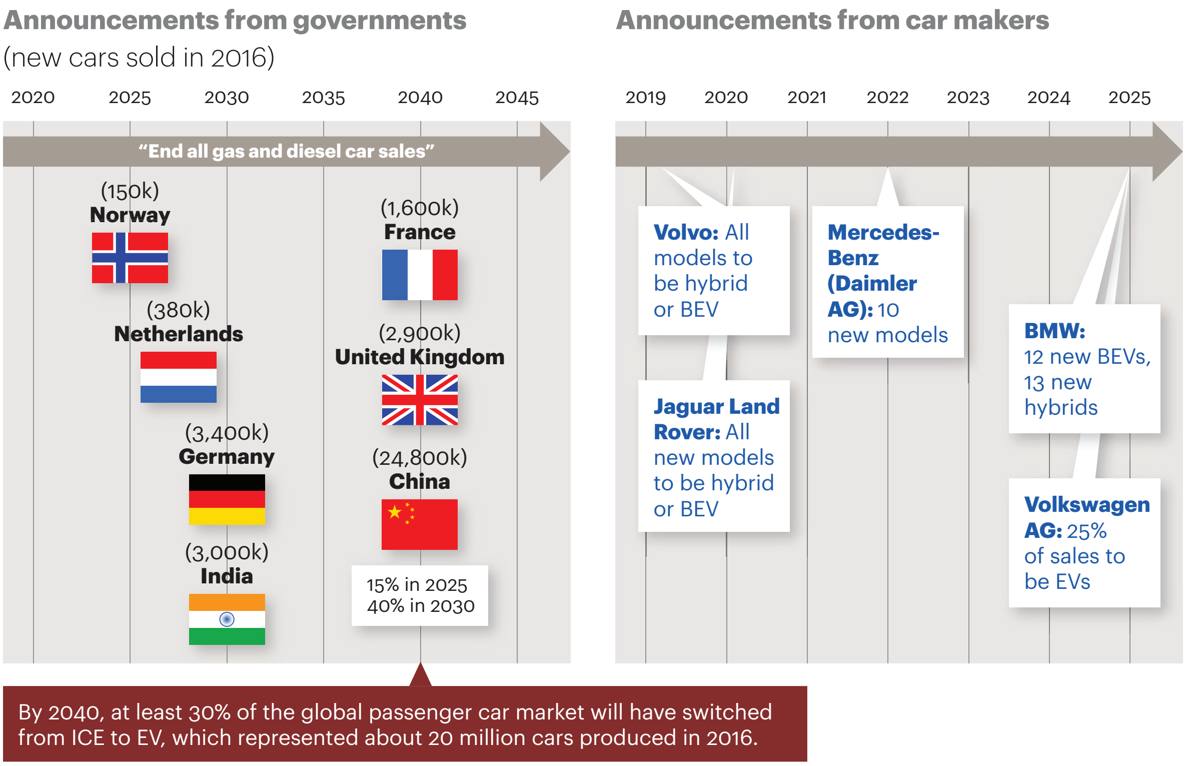
Nobody's sure how fast demand for electric vehicles (EVs) will rise in the next two decades, but the global market is on the cusp of exponential, explosive growth. Encouraged by governments and city authorities aiming to replace internal combustion engine vehicles (ICEVs) with cleaner alternatives, manufacturers are busy making EVs. And consumers are queueing up to buy them.

> Three underappreciated risks to growth are scarcity of natural resources, recycling of batteries and CO_2 emissions reductions.

But three problems present significant and underappreciated risks to growth: the scarcity of natural resources used to make batteries; the establishment of effective systems and processes for recycling or reusing batteries; and the risk that widespread use of battery electric vehicles (BEVs) may not actually reduce CO_2 emissions below the level that would be associated with the continued use of ICEVs.

Consider the projections for market growth first. Ambitions vary by country (see figure 1). France and the UK, for example, want all new cars sold by 2040 to be ICEV-free. India wants to achieve

Figure 1
A number of governments and car makers have ambitious plans for electric vehicles

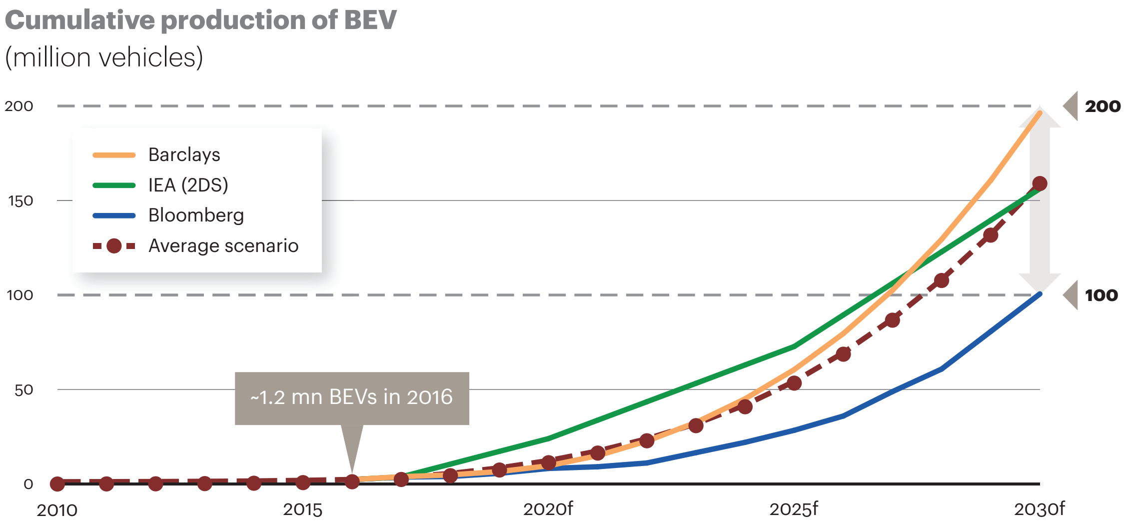


Notes: ICE is internal combustion engine. EV is electric vehicle. BEV is battery electric vehicle.
Source: A.T. Kearney Energy Transition Institute

the same goal, but 10 years earlier. China is also gearing up for growth: by 2025, 15 percent of its car fleet will be electric, rising to 40 percent by 2030. Government announcements to date indicate that, by 2040, at least 30 percent of global passenger cars will be BEVs or hybrid electric vehicles (HEVs). At today's rate of production—67 million cars of all types came off production lines in 2016—that would imply annual production in 2040 of 20 million EVs. But, of course, total car production won't stand still. Far from it.

So how big can the EV market get? Forecasts vary (see figure 2). There were 1.2 million BEVs on the roads in 2016. By 2030, the number could reach 200 million, says Barclays. The International Energy Agency (IEA) makes a similar projection. Information company Bloomberg, more cautious, predicts a still-vertiginous rise to 100 million by 2030.

Figure 2
Predictions vary for the future of the battery electric vehicle market



Note: BEV is battery electric vehicle.
Sources: IEA *Global EV Outlook 2017*, BNEF *Electric Vehicle Outlook 2017*, Barclays Equity Research, *The €180bn EV Capex Opportunity;* A.T. Kearney Energy Transition Institute analysis

Car makers, meanwhile, are transforming vision into reality. BEVs will account for a quarter of VW's sales by 2025, the company says. And after 2020, you won't be able to buy a new Volvo that isn't a BEV or a HEV. Many other companies already produce EVs and have an expanding portfolio of electric models in the works. Those that haven't jumped on the electric bandwagon soon will.

But the EV industry's success depends on numerous factors beyond manufacturing electric vehicles. Many concern infrastructure, where familiar roadblocks to development include guaranteeing electricity supply from environmentally safe and sustainable resources, building grids equipped to charge millions of vehicles simultaneously, and establishing nationwide networks of recharging points.

But batteries themselves also present threats to progress—threats that are often overlooked. This article focuses on three in particular. The first concerns the availability of natural resources: if demand for EVs evolves as expected, the supply of battery materials will struggle to keep pace. The second concerns the environment—what to do with millions of old batteries. The third considers the CO_2 emissions reductions that might be achieved by switching from ICEVs to BEVs.

Production of Batteries from Scarce Natural Resources

BEV batteries, generally lithium-ion (Li-ion) or nickel-metal hydride (NiMH), contain lithium and cobalt, along with other raw materials. Both metals face supply constraints that could impede the electric car's progress.

Cobalt is in particularly short supply. World reserves, the amount estimated to be economically producible today with existing technology, amount to 7 million tonnes, representing only 57 years of production at 2016's level, according to the US Geological Survey. But if 300 million large BEVs were produced with this technology, a modest proportion even of the 1.2 billion cars on the roads today, we estimate that current global cobalt reserves would be exhausted. And, in the real world, car batteries won't monopolize supply; other industries—medicine, superalloys, steel manufacturing, and many more—need cobalt too. In fact, only about 50 percent of global cobalt production is used for rechargeable batteries, according to the Cobalt Institute.

> If 300 million large BEVs were produced with this technology, we estimate that current global cobalt reserves would be exhausted, and the supply chain bottle neck of lithium would likely persist.

Recent production and pricing statistics reflect cobalt's limitations as a battery material. Since 2014, production has flat-lined, and in the past 18 months, the price has risen by 200 percent. Although larger resources are known to exist, the technology for extracting them is immature and there is no guarantee that they will ever be economically recoverable.

According to a *Financial Times* article, "Amnesty warns on use of child labour in cobalt mining," in November 2017, cobalt mining has been tarnished by human-rights abuses. Half of the world's production in 2015 came from the Democratic Republic of Congo. Finding alternatives to cobalt is critical.

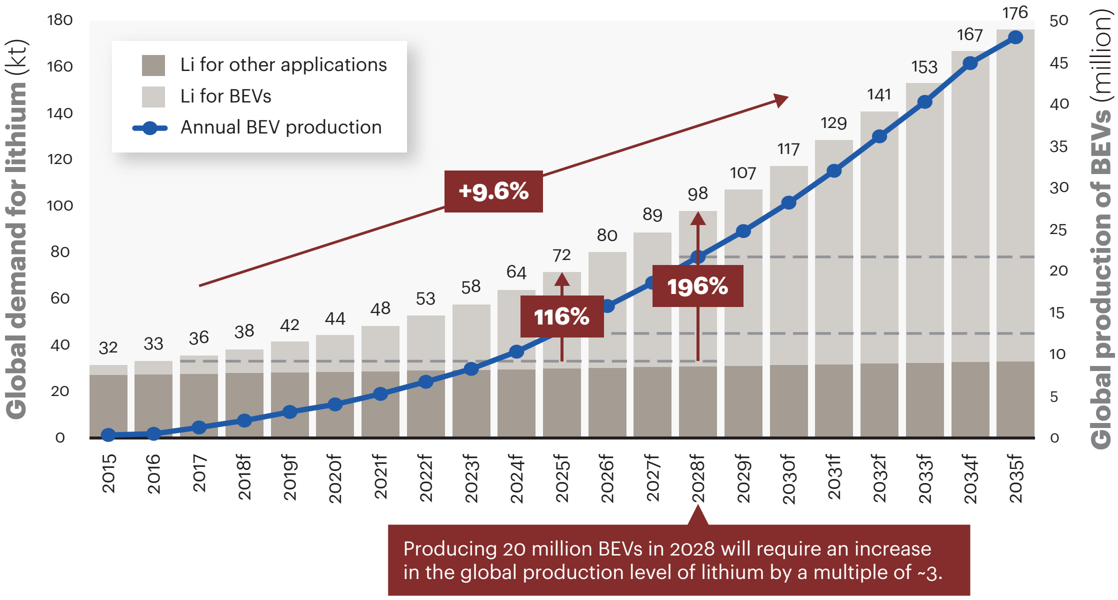
Lithium is sourced from a more politically stable spread of countries. And there's more of it. USGS estimates global lithium reserves amount to 14 million tonnes, which would last 400 years if used at the 2016 consumption rate. Unproved lithium resources are much higher too—up to 40 million tonnes.

But if lithium resources are not a constraint, the rate of production is. Since 2013, global lithium production has risen at 7 percent a year, but we estimate miners need to accelerate output growth to 9 percent a year to keep up with demand (see figure 3 on page 4). Rising demand and tight supply have led to price increases: in 2015, prices in most markets rose by 40-60 percent; in the same year, the price in China tripled.

Car battery makers face competition for lithium too. In 2015, EVs consumed 14 percent of all lithium produced. Traditional battery markets absorbed 25 percent, non-battery markets 60 percent, and the remaining 1 percent was split between electric bicycles and energy storage.

Figure 3

Global lithium demand will increase dramatically as BEV production grows



Notes: BEV is battery electric vehicle. Figures assume that other sectors' demand for lithium will not exceed 1% per year. Figures assume 22.3 kWh per BEV and 0.13kg Li / kWh or ~3kg Li / passenger car.

Sources: IEA *Global EV Outlook 2017*, BNEF *Electric Vehicle Outlook 2017*, Barclays Equity Research, *The €180bn EV Capex Opportunity*; A.T. Kearney Energy Transition Institute analysis

In order for global BEV production to reach 12.5 million cars in 2025, an average of the projections by Barclays, Bloomberg, and the IEA, we estimate lithium production will need to more than double in under 10 years, and it would need to almost triple by 2030. Goldman Sachs forecasts a six-fold increase in lithium demand by 2030.

> In a few extreme cases, charging BEVs from power derived from coal- or oil-fired electricity plants could lead to a counterintuitive increase in CO_2 emissions compared with continued use of ICEVs.

The problem is even more serious if HEVs are considered. In addition to the 1.2 million BEVs on the roads in 2016, there were 0.8 million HEVs in use and their numbers are also rising. HEV batteries are smaller, but they will place further strain on natural resources.

New natural elements will be introduced into lithium batteries. But even if alternative materials alleviate or eliminate the need for cobalt, most will still require lithium. Lithium-silicon batteries are a short-term option, and lithium-sulfur, lithium-air, and solid-state batteries have potential in the longer term. But fully lithium- and cobalt-free technologies, such as the vanadium redox flow battery, would fall short of BEV requirements and face resource shortages of their own. The lithium supply chain's bottleneck is therefore likely to persist.

Recycling and Reuse of Batteries

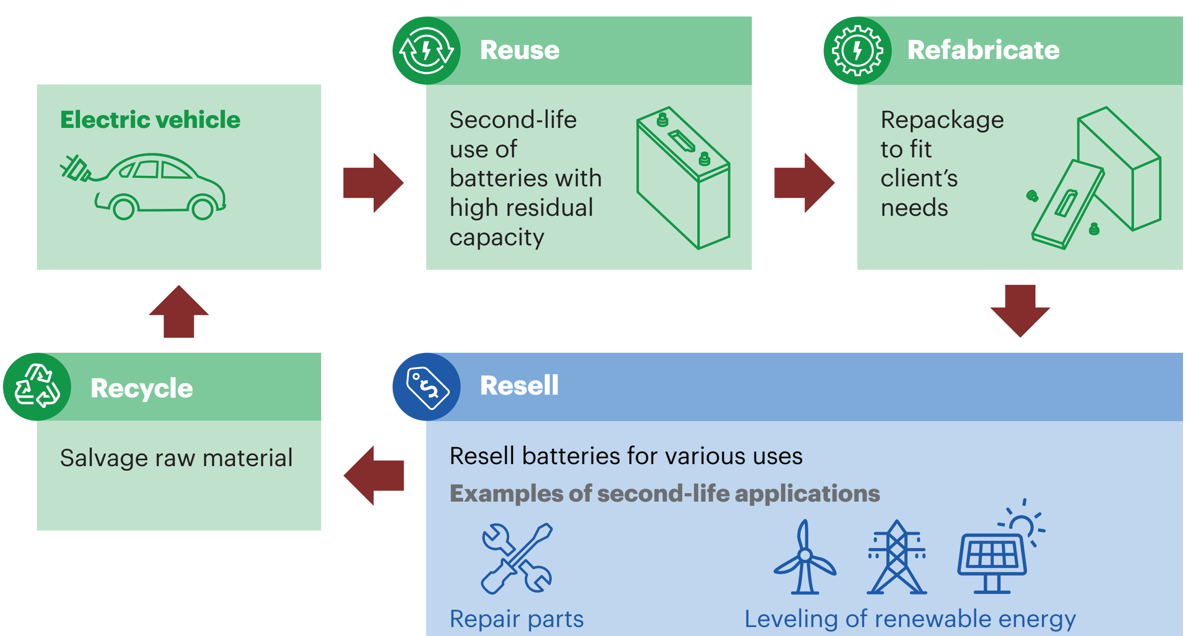
Meanwhile, with the first generation of electric vehicle batteries reaching end-of-life, the market for used BEV batteries is on the brink of take-off. This will require the engineering of a reverse supply chain for collecting, refurbishing, and recycling vast numbers of batteries.

That might not seem pressing today—the industry is in its infancy and most electric cars still have young, healthy batteries. But, if left unaddressed, it will quickly become a problem. Data is scarce. Nissan sold the first fully electric vehicle in 2010 and, so far, has only had to recycle a handful of batteries. But most car batteries are likely to need replacing after 7-10 years of service, when storage capacity falls to 70–75 percent of the manufacturer's spec; efficiency, acceleration, performance, and reliability are impaired, and they cease to be viable. However, the ultimate end-of-life is estimated at around 50 percent of initial capacity, so batteries unfit for vehicular use would still have a few years of life left and would be suitable for the lower cycling requirements of stationary applications. This would not only lower the cost of batteries by increasing their commercial value at the end of their BEV life, but it would also temporarily diminish the environmental problem of battery recycling.

Consider all that just in the context of the EVs sold last year. Some batteries from the 460,000 or so 2016-vintage EVs will be due for replacement around 2025. Shortly after that, all of them will. And that's only one year's production. In 2017, as many as 1.2 million electric cars are likely to have been sold, and numbers will only rise.

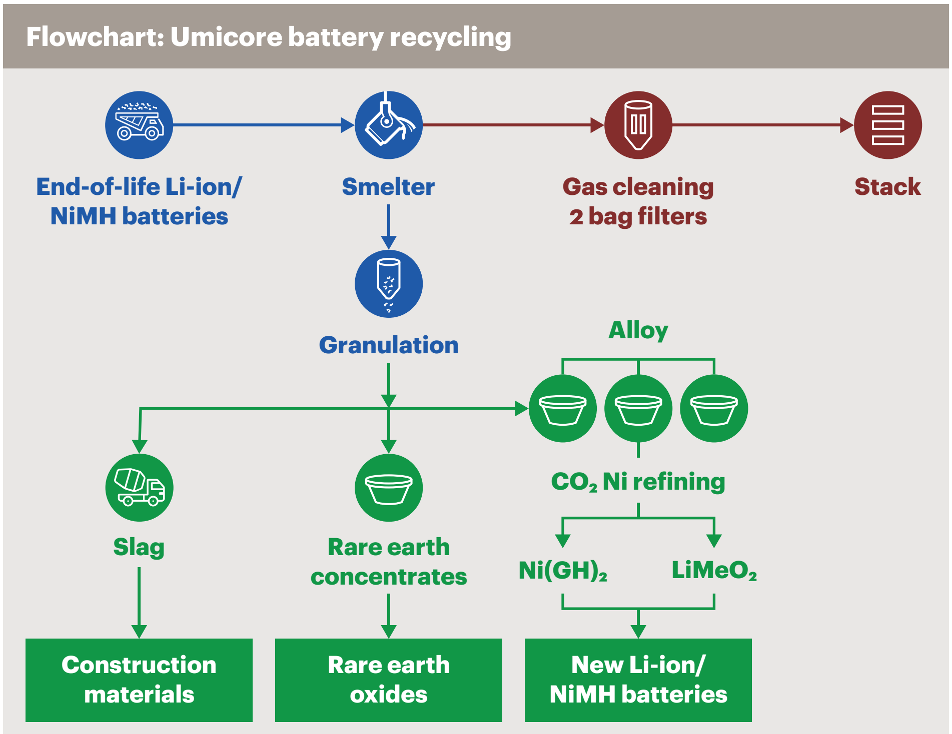
There are two ways of dealing with used batteries: reuse (see figure 4) and recycling (see figure 5 on page 6). Recycling involves dismantling batteries and recovering chemical components such as lithium and cobalt. Reuse, a much more practical alternative in the near term, involves identifying and replacing faulty cells to prolong battery life.

Figure 4
Life cycle of an electric vehicle battery with a second life



Sources: Ademe, *Study on the second life batteries for electric and plug-in hybrid vehicles*, 2011; A.T. Kearney Energy Transition Institute, *Electricity Storage FactBook*, 2018

Figure 5
Umicore owns one of the world's largest BEV battery recycling installations



Sources: Umicore website; A.T. Kearney Energy Transition Institute analysis

EV battery recycling barely exists as an industry and is only cost-competitive for batteries that contain high amounts of expensive metals such as cobalt. Lithium-ion batteries can't yet be recycled profitably. Even in China, where industrial costs are generally low, the value of materials recovered from recycled Li-ion batteries is around 95 percent of the cost of recycling. Neither is recycling lithium for new batteries economical: the purification process costs more than purchasing new lithium.

Eventually, probably beyond 2025, the economics of recycling will improve, as used batteries become commonplace and secondhand battery markets take root. Other, less predictable forces, such as possible declines in the cost of raw materials or the emergence of new battery compositions, may help too. In the meantime, however, governments must support the industry through regulation and subsidies to ensure decent returns. Their planning will certainly benefit from the predictability of how the market will evolve, since it will mirror EV-market development with a lag period of 8-15 years.

There are already some signs of progress in recycling. Belgian recycling group Umicore owns one of the world's largest dedicated recycling installations for Li-ion and NiMH batteries. Located in Hoboken, Belgium, the plant can process 7,000 tonnes a year—equivalent to about 35,000 EV batteries. US market leader Retriev has three sites in North America that recycle Li-ion batteries and others, including NiMH, NiCad, and lead acid. Tesla's Gigafactory in Nevada, which should reach production capacity of 35 gigawatt hours (GWh) in 2018, will have on-site recycling and refurbishment facilities. Northvolt, a start-up, is seeking funding for what would be Europe's largest Li-ion battery factory, a 32 GWh plant in Sweden that will incorporate recycling and refurbishment capacity. Other projects are planned, and many more will be needed.

If recycling has a long way to go, a more realistic way forward for the time being is to repurpose old car batteries for electricity storage, in which diminished capacity matters less.

The economics and business case are compelling. Demand for energy storage is almost limitless, as utilities and network operators seek to adapt to the proliferation of intermittent renewable energy and to new applications, such as fleets of EVs, by increasing the flexibility and efficiency of power supply and improving grid stability. The cost of refurbishment, which arises mainly from the work involved in testing and replacing faulty cells, is low—as little as $20 per kilowatt hour (kWh) of a battery's nameplate capacity, says National Renewable Energy Laboratory, a renewable-energy research company funded by the US Department of Energy. Demand for new Li-ion batteries for energy storage is already plentiful; refurbished batteries are a cheaper alternative and, as such, will be attractive to a new industry seeking to establish itself.

BEV batteries are versatile too (see figure 6). They are suitable for energy storage from grid-level applications to residential ones, providing network operators with back-up supply for smoothing out intermittent supply from renewables; homeowners with storage for electricity generated in solar panels; and data centers and other businesses with uninterruptible power.

Figure 6

Current energy storage solutions by battery electric vehicle OEMs are varied

Applications	New batteries	Used batteries	
Home storage	**Tesla** (14 kWh) **Mercedes** (2.5-20 kWh)	**Nissan** (24 kWh) Reused Leaf batteries	**BMW** (22 or 33 kWh) Reused BMW i3 batteries
Large scale	**Tesla** (California) (20 MW)	**BMW / Vattenfall / Bosch** (Hamburg) (2.8 MWh) Reused batteries from 100 electric vehicles	

Notes: OEM is original equipment manufacturer. kWh is kilowatt hours. MW is megawatts. MWh is megawatt hours.
Source: A.T. Kearney Energy Transition Institute

Some refurbished EV batteries are already in use. Batteries from Nissan's Leaf and BMW's i3 model, for example, have been built into domestic powerwalls. And, at the utility scale, a consortium of Vattenfall, BMW, and Bosch has assembled more than 2,600 battery modules from more than 100 electric vehicles to create a 2-megawatt (MW) power station in Germany with storage capacity of 2.8 MWh.

If the contribution of refurbished batteries to energy storage is modest at first, certainly in the context of global electricity supply, it will grow quickly. Car manufacturers may be producing 20 million EVs a year by 2030, a very large number of cars, all with batteries that will eventually find their way into the secondhand market.

Whereas specialist third-party recycling companies skilled in process chemistry and manufacturing processes will lead the way in recycling, refurbishment will be the domain of companies with electrical and industrial know-how. Among them, original equipment manufacturers (OEMs) will predominate by virtue of their pivotal position in used-battery supply, with links both to dealerships and customers. Access to proprietary battery performance data will also help them select the best batteries for refurbishment and cut down on time spent on testing. Several BEV OEMs have already invested in battery-manufacturing facilities incorporating refurbishment capacity.

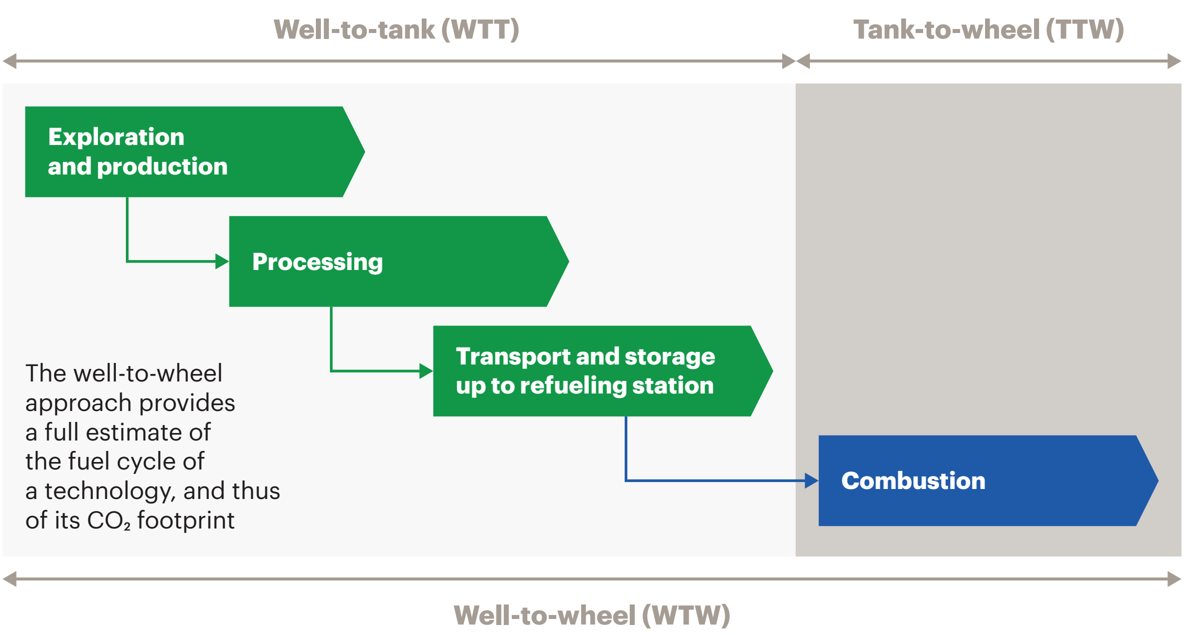
Eventually, though, all batteries—including refurbished ones—must be recycled. This calls for robust regulation—in the form of strictly enforced anti-dumping and pollution laws, for example—to protect the environment from toxic materials. Some countries are already on the right track, with legislation governing disposal of chemicals such as lithium. Many, however, are not.

CO_2 Footprint: BEVs Versus ICEVs

It is generally thought that BEVs will produce less CO_2 than ICEVs; electric engines are more efficient than ICEs and can be recharged during off-peak periods in electricity supply, when electricity is generally generated with less-CO_2-intensive power sources.

A vehicle's CO_2 footprint should be calculated on a life-cycle basis, accounting for (1) CO_2 emitted as a result of vehicle manufacturing and infrastructure construction or decommissioning and (2) CO_2 emitted as a result of the utilization of the vehicle itself, a factor of the primary energy source used and how efficiently the engine transforms that energy into motion—the well-to-wheels CO_2 budget (see figure 7). Virtually infinite combinations of vehicle types, electricity generation mixes, and vehicle uses complicate such calculations.

Figure 7
The well-to-wheel approach



Source: A.T. Kearney Energy Transition Institute

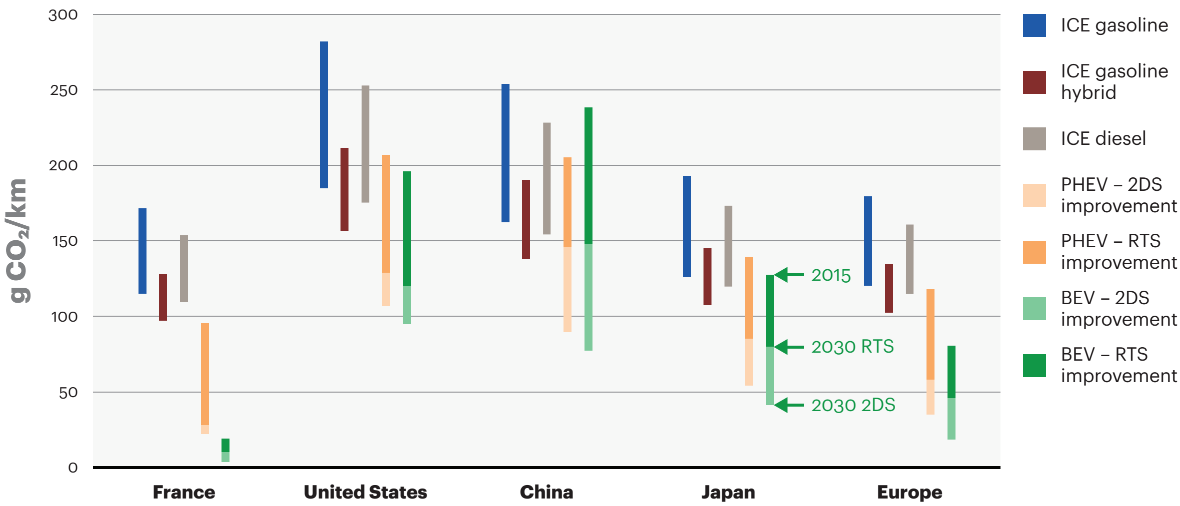
According to a recent study by IVL Swedish Environmental Research Institute, CO_2 emissions resulting from the manufacture of Lithium-ion batteries and the processing of battery materials range from 150 to 200 kg CO_2eq/kWh. For a 25-kWh battery, this implies a CO_2 budget of 3,750 to 5,000 kg CO_2eq. If the battery lasted for 125,000 km of use, a reasonable assumed average over 7 years, its manufacturing-related CO_2 budget would be in the region of 3 to 4 g CO_2eq/km—small, but not negligible.

Differences between ICEVs and BEVs become less obvious when analyzed on a life-cycle basis, however. The IEA's Global EV Outlook 2017, which compares the well-to-wheel performance of a selection of light-duty vehicles in various countries, highlights the importance of the power mix in determining overall CO_2 emissions (see figure 8). In France, where emissions per kWh of electricity generated are low (~60g CO_2/kWh), there is a clear benefit to using BEVs instead of ICEVs. But in countries with higher CO_2 emissions per kWh (up to 850g CO_2/kWh), ICEVs might actually be preferable. *Financial Times* recently drew a similar conclusion, showing that in the US Midwest a Tesla model S released more CO_2 than a small ICEV over its lifetime. Analysis should therefore be done on a country-by-country or regional basis.

Furthermore, because the mass deployment of BEVs will result in a steep increase in electricity demand, additional low-carbon power-generation technologies will be essential if the environmental benefits associated with the electrification of mobility are to be captured. A 30 percent increase in electricity supply would be necessary to feed a fully electric personal car fleet in the US, for example. Indeed, in a few extreme cases, charging BEVs from power derived from coal- or oil-fired electricity plants could lead to a counterintuitive increase in CO_2 emissions compared with continued use of ICEVs.

Figure 8

The benefits of battery electric vehicles versus internal combustion engine vehicles differ by country



Notes: The upper limit of each bar shows the well-to-wheel (WTW) CO_2 emissions estimated for each powertrain technology in 2015. The lower limit of the dark shading in each bar shows the WTW CO_2 emissions from the technology in 2030, assuming technology and grid decarbonization improvements aligned with the RTS. The bottom of the light-shaded part of the bars shows the WTW CO_2 emissions in 2030, assuming technology and grid decarbonization improvements aligned with the 2DS. Vehicle powertrain characteristics reflect the regional assumptions of IEA (2017a). PHEV CO_2 emissions are calculated on the basis of an electric driving rate of 30% of the total mileage in 2015 and an electric driving rate of 80% of the total mileage in 2030.

Notes: ICE is internal combustion engine. PHEV is plug-in hybrid electric vehicles. 2DS is 2°C scenario. RTS is reference technology scenario. BEV is battery electric vehicle.

Source: Internation Energy Agency, *Global EV Outlook 2017*

Proceed with Caution

Assumptions about how the BEV market will evolve in terms of size, and about the secondhand battery market that will follow in its wake, remain speculative. Uncertainties over the availability of materials or the industry's capacity to produce them, as well as the emerging endeavor of configuring grids for mass EV deployment, push forecasting into the realm of guesswork. Other considerations muddy the outlook further still: fuel-cell cars may make inroads into the BEV market, or consumer behavior could shift—a surge in carpooling, for instance, might moderate demand for EVs.

Yet, given the ambition of many countries to phase out ICEVs, it's safe to say electric-car and battery markets are on the brink of explosive growth. The world needs strategies for an industrial and technological transition on such an epic scale that are scientifically and technically practical, industrially possible, economically viable, and environmentally sound.

In collaboration with various branches of industry—from miners to battery makers and car manufacturers—governments must manage the growth of these industries with care, improving power mixes to safeguard the environmental benefits of switching to BEVs, regulating to avoid pollution from used battery waste and to encourage appropriate technologies, while providing support for recycling and other nascent areas of business. In the interests of effective climate-change mitigation, sustainable industry growth, and consumer satisfaction, a holistic approach to managing energy systems and technologies has become more vital than ever.

Authors

Romain Debarre, managing director, romain.debarre@energy-transition-institute.com

Daniel Gilek, consultant
daniel.gilek@atkearney.com

About the A.T. Kearney Energy Transition Institute

The A.T. Kearney Energy Transition Institute is a nonprofit organization. It provides leading insights on global trends in energy transition, technologies, and strategic implications for private sector businesses and public sector institutions. The Institute is dedicated to combining objective technological insights with economical perspectives to define the consequences and opportunities for decision-makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders. For more information visit www.energy-transition-institute.com.

References

[1] Académies des Sciences, La question de la transition énergétique est elle bien posée dans les débats actuels?, 2017

[2] Argonne National Laboratory, Well-to-Wheels Analysis of Energy Use and Greenhouse Gas Emissions of Plug-In Hybrid Electric Vehicles, 2010

[3] Barclays Equity Research, *The €180bn EV Capex Opportunity*, 2017

[4] Benchmarkminerals, 2016 Benchmark mineral

[5] Commission for Environmental Cooperation, Environmentally Sound Management of End-of-Life Batteries from Electric-Drive Vehicles in North America, 2015

[6] *Financial Times*, Lack of ethical cobalt undermines Tesla debt issue, August 2017

[7] *Financial Times*, Electric cars' green image blackens beneath the bonnet, November 2017

[8] *Financial Times*, Amnesty warns on use of child labour in cobalt mining, November 2017

[9] BNEF, Electric Vehicle Outlook 2017

[10] Deutsche Bank Markets Research, *Charging the car of tomorrow*, 2016

[11] Deutsche Bank Markets Research, *Welcome to the Lithium-ion Age*, 2016

[12] IEA, Global EV Outlook 2017

[13] IVL Swedish Environmental Research Institute, The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries, 2017

[14] NREL, *Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries*, 2015

[15] US DoE, *Maintenance and Safety of Hybrid and Plug-In Electric Vehicles*

[16] US DoE, Plug-In Electric Vehicle Handbook for Consumers, 2015

[17] USGS, National Minerals Information Center, 2017

[18] World Bank Publications, The Growing Role of Minerals and Metals for a Low Carbon Future, 2017

[19] World Energy Council, World Energy Resources—E-Storage, 2016

A.T. Kearney | Energy Transition Institute

A.T. Kearney is a leading global management consulting firm with offices in more than 40 countries. Since 1926, we have been trusted advisors to the world's foremost organizations. A.T. Kearney is a partner-owned firm, committed to helping clients achieve immediate impact and growing advantage on their most mission-critical issues. For more information, visit www.atkearney.com.

Americas	Atlanta Bogotá Boston Calgary Chicago	Dallas Detroit Houston Mexico City New York	San Francisco São Paulo Toronto Washington, D.C.
Asia Pacific	Bangkok Beijing Brisbane Hong Kong Jakarta	Kuala Lumpur Melbourne Mumbai New Delhi Perth	Seoul Shanghai Singapore Sydney Tokyo
Europe	Amsterdam Berlin Brussels Bucharest Copenhagen Düsseldorf Istanbul Lisbon	Ljubljana London Madrid Milan Moscow Munich Oslo Paris	Prague Rome Stockholm Vienna Warsaw Zurich
Middle East and Africa	Abu Dhabi Doha	Dubai Johannesburg	Riyadh

For more information, permission to reprint or translate this work, and all other correspondence, please email: insight@atkearney.com.

The signature of our namesake and founder, Andrew Thomas Kearney, on the cover of this document represents our pledge to live the values he instilled in our firm and uphold his commitment to ensuring "essential rightness" in all that we do.