Batteries for EVs

Breakthroughs and Challenges

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Key Points in This Report:

- Battery prices continue to decline for EVs, but will not reach $100/kWh until around 2030. Reaching this level will help EV costs reach parity with ICEVs.
- My view based on my research and discussions with numerous experts for this report is that this is going to happen, but from incremental improvements to lithium-ion batteries (LIBs).
- Other technology options will be available after 2030.
- Massive scale up of battery factories will help drive prices further downward. The major expansion is happening in China.
- The recycling regime(s) for EV batteries have not been figured out. This includes the regulatory regime in many countries as well as the business case/supply chain. I believe based on discussions with experts that this will be sorted out in the next five years or less.

Introduction

There are a number of challenges to widespread EV adoption around the world, many of which I have written about for the last three years, including their high costs, consumer preference for the internal combustion engine vehicle (ICEV), the high costs to governments to bring EVs to market and encourage consumer uptake, and the lack of infrastructure, among other issues. (See reports Jan. 15, 2019; June 21, 2018; Mar. 28, 2018) This report focuses squarely on batteries for EVs, in particular future battery breakthroughs and expected manufacturing over the next 10 years.

Today typical batteries used in EVs are based on lithium-ion technology which has in the last few years reached a development level enabling the design of vehicles that are beginning to match (and some would argue, surpass) the performance of internal combustion engine vehicles (ICEVs). Current battery packs for light-duty applications have gravimetric energy densities of 200 Watt-hours per kilogram (Wh/kg) and volumetric pack energy densities of 200-300 Watt-hours per liter (Wh/l), according data cited by IEA.[1] Battery performance has improved and is continuing to improve while battery lifetimes are getting longer as well. In fact, battery lifetime now is as long as the expected lifetime of a car or about 175,000 km (109,000+ miles) of driving. Battery chemistry has improved, charging times are faster and manufacturing is growing, as shown in this report.

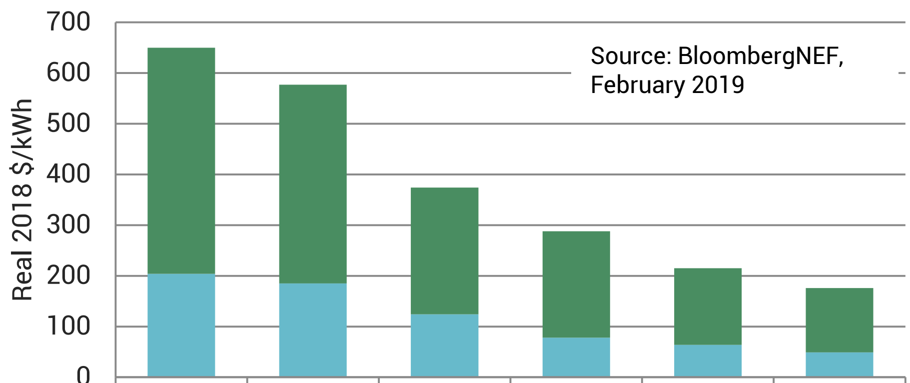
As a result, battery prices are continuing to decline, shown in Figure 1. Between 2010-2018, battery prices declined 85%; between 2017-2018, 18%, according to Bloomberg New Energy Finance's (BNEF) annual battery survey. However, to really make EVs price-competitive with ICEVs on an unsubsidized basis, EV battery packs need to fall to a cost of $100/kWh.[2] Experts I talked to for this report say that will most likely happen around 2030. That's challenge number one: getting prices down at that level, or even lower. Experts that I talked to in the auto and battery industries believe that will happen, even with the recent spike in prices of materials such as lithium and especially cobalt.

[1] International Energy Agency, "EV Outlook 2018," June 2018 available https://webstore.iea.org/global-ev-outlook-2018 (hereinafter "IEA").

[2] See Baes, et al., Arthur D. Little, "Future of Batteries: Winner Takes All?", May 2018 available at http://www.adlittle.com/sites/default/files/viewpoints/adl_future_of_batteries-min.pdf.

The consensus was also that LIBs will remain the battery option of choice for EVs for now (10-15 years or more) and that they will be further improved over time. More mass manufacturing planned, the "Gigafactories" will further drive down costs. Another big challenge however, discussed in the section below, is recycling the batteries. There is the challenge of figuring out the "afterlife" of an EV battery and what that supply chain will look like, and then there is the challenge of setting regulations governing the recycling regime. My view based on research and interviews with experts is that this will be surmounted.

Figure 1: LIB Prices 2013-2018



	2013	2014	2015	2016	2017	2018
Cell	446	392	250	210	151	127
Pack	204	185	124	78	64	49

Future Battery Breakthroughs

Lithium-ion is expected to remain the technology of choice in batteries for the next decade[3], when it is expected to take advantages of a number of improvements to enhance battery performance.[4] Other technology options are expected to become available after 2030, shown in Figure 2.

The main developments in cell technology that are likely to be deployed in the next few years include:

- For the cathode[5], reducing cobalt content in existing cathode chemistries, aiming to reduce cost and increase energy density, i.e. from today's nickel manganese cobalt (NMC) 111 to NMC 622 by 2020, or

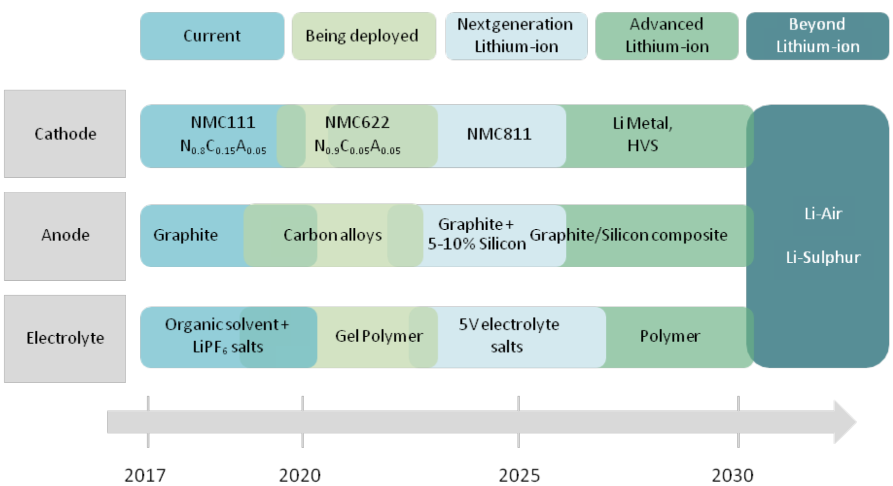
[3] "Lithium Ion battery is the mainstream battery technology in current and the main direction in future. Their special excellent property has become the focus of the patent application. Based on the analysis, we can predict that the Lithium Ion battery will not be replaced by others in a longer period of time. In addition, power battery is equipped with a broad market prospect. The development of battery technology of EVs is not only need to rely on the support of national policy, but also on the integration of multidisciplinary and the cooperation of interdisciplinary. Finally, there is no doubt that China's battery technology is still in initial stage of innovation at present. Competed with the international level, China still has a large gap. Therefore, strengthening R&D investment and catching up with advanced international level should be the long-term development strategy of China's EV battery technology." Zhang, et al., "Analysis of Research and Development Trend of the Battery Technology in Electric Vehicle with the Perspective of Patent," Energy Procedia, May 2017 at https://www.sciencedirect.com/science/article/pii/S1876610217310172.

[4] See IEA at footnote 1.

[5] For members who may not be as familiar, LIBs contain an anode and a cathode in an electrolyte and the electrical current in the battery is generated from ions traveling from the anode to the cathode.

from the 80% nickel and 15% cobalt of current lithium nickel cobalt aluminum oxide (NCA) batteries to higher shares of nickel.

- For the anode, further improvement to the graphite structure, enabling faster charging rates.
- For the electrolyte, the development of gel-like electrolyte material.[6]



Notes: HVS = high voltage spinel. The diagram shows the likely beginning of commercialisation of a given technology.
Sources: IEA analysis based on Meeus (2018); Nationale Plattform Elektromobilitat (2016); NEDO (2018); Howell (2016); Pillot (2017).

These advancements are expected to improve density and further bring down the price of batteries, which is expected to bring down the costs of EVs. I note with respect to the first point that the battery and auto industry have a huge incentive to move as quickly away from cobalt as possible to avoid the human rights issues that have arisen as mining in the Democratic Republic of Congo (DRC) has skyrocketed.[7] There is also a potential supply crunch coming for both lithium and especially cobalt. Today's LIB market already uses over 40% of the world's mined cobalt, according to Global Energy Metals (GEM).[8] And, an EV requires 10kg of cobalt, 1,000 times more than a battery in a smart phone.

A study released in 2018 lead by MIT, notes that key battery constituents such as manganese, nickel, and natural graphite, have sufficient supply to meet the anticipated increase in demand for LIBs.[9]

[6] Dr. Marcel Meeus, Energy Materials Industrial Research Initiative (EMRI), Review of the Status of Main Chemistries for the EV Market, March 2018 available at https://www.iea.org/media/Workshops/2018/Session1MeeusSustesco.pdf.

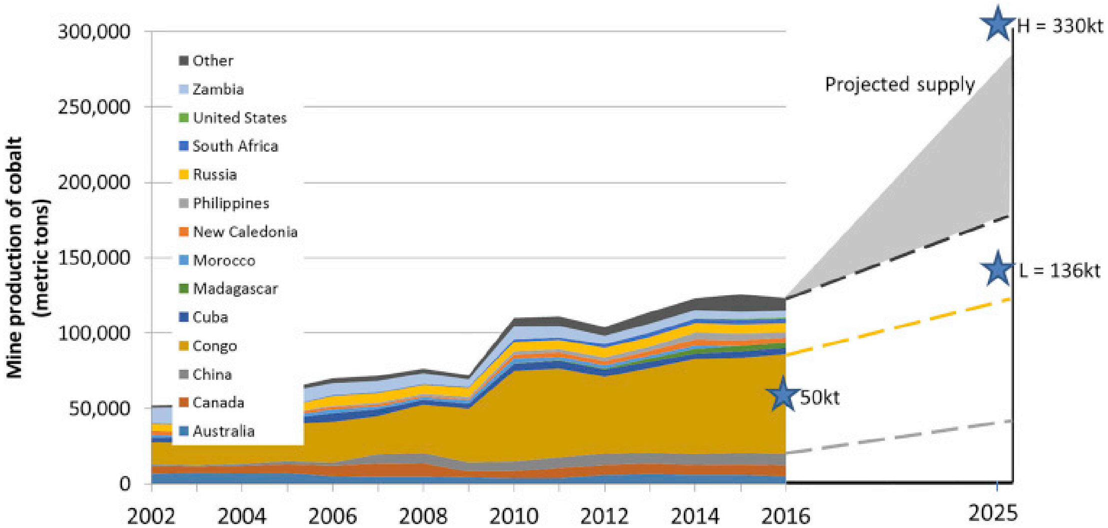
[7] See Scott Peterson and Alexandra Wexler, The Wall Street Journal, "Despite Cleanup Vows, Smartphones and Electric Cars Still Keep Miners Digging by Hand in Congo," Sept. 13, 2018 at https://www.wsj.com/articles/smartphones-electric-cars-keep-miners-digging-by-hand-in-congo-1536835334. It has been very difficult to develop transparent, sustainable supply chains that can be verified and corruption in the DRC and from countries like China abound.

[8] Cobalt prices have recently declined, from a high of US$43.60/pound in May 2018 to US$17.85/pound in February 2019. See Amrith Ramkumar, Wall Street Journal, "Investors Get Burned After Betting on Electric-Car Metals," Feb. 17, 2019 available at https://www.wsj.com/articles/investors-get-burned-after-betting-on-electric-car-metals-11550404801.

[9] Olivetti, et al., "Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals," Joule 1, 229–243, Oct. 11, 2017 available at https://www.cell.com/joule/fulltext/S2542-4351(17)30044-2.

There may be challenges in rapidly scaling the use of materials associated with lithium and cobalt in the short term. For lithium, the MIT authors say the issue is not one of availability, but of ramping up production in a timely enough manner to meet growing demand.

Figure 3: MIT Lithium Supply Outlook to 2025 (Source: MIT)



For cobalt, the issue is the geopolitical risk since 60% of the world's supply comes from the DRC. GEM notes that China alone is 90% reliant on DRC's cobalt supply worth about US$1.2 billion.[10] IT's outlook for cobalt through 2025 is presented in Figure 3.

The minimum in supply projection (black dashed line) is based on documented growth in mined and refined capacity in China and the DRC (shown by gray and gold dashed lines, respectively) assuming constant production in the other countries. This provides a lower projection of 180 kilotons (kt) in 2025. A more aggressive supply projection (shown in gray) assumes growth in supply up to 290 kt in 2025. The stars indicate the demand for cobalt from the LIB industry in 2016 with projections for its low (L) and high (H) scenarios in 2025. The MIT team says that while supply will meet demand for the lower estimates of demand for LIBs, there is a potential for availability concern if there is rapid EV adoption.

Next Generation Batteries

The next generation of Li-ion batteries (LIBs) entering the mass production market around 2025 is expected to have low cobalt content, high energy density and NMC 811 cathodes. Silicon can be added in small quantities to the graphite anode to increase energy density by up to 50%, while electrolyte salts able to withstand higher voltages will also contribute to better performance.[11]

[10] Tammy Klein, Future Fuel Outlook, "Cobalt & Lithium Supplies for EVs May Be At Risk," Mar. 28, 2018 at http://futurefuelstrategies.com/2018/03/28/cobalt-lithium-supplies-for-evs-may-be-at-risk/. China was the world's leading producer of refined cobalt and the leading supplier of cobalt.

[11] "However, a change in the material used in most current battery anodes—graphite—towards anodes incorporating silicon results in huge increases in battery capacity, up to 30%. [C]ompanies will be rolling out consumer batteries with lithium-silicon batteries within two years." See Christopher Mims, The Wall Street Journal, " The Battery Boost We've Been Waiting for Is Only a Few Years Out," Mar. 18, 2018, available at https://www.wsj.com/articles/the-battery-boost-weve-been-waiting-for-is-only-a-few-years-out-152137440.

In the 2025-2030 period, technologies that promise significantly higher energy densities are likely to begin entering the market and would push the limits of LIBs (advanced Liion). For example, lithium metal cathodes are a potential avenue for LIBs with improved performance without relying on cobalt and anodes made of silicon composite might enter the design. In this period, solid-state[12] electrolytes might also be introduced and further improve energy density and battery safety.[13] BMW and Toyota are both working on solid-state batteries.

Another 2018 report noted the industry has 10 years to develop alternative battery chemistry.[14] "The pace of advance is slowing [for LIBs] as conventional technology approaches fundamental limits. The amount of charge that can be stored in gaps within the crystalline structures of electrode materials is nearing the theoretical maximum. Projected market growth will not lower prices substantially — the markets are already large."

The authors advocate for alternative types of electrodes based on cheap, common metals such as iron and copper need to be developed urgently. "In our view, the most promising candidates involve 'conversion materials', such as copper or iron fluorides and silicon. These store lithium ions by bonding chemically with them. But the technology is still at an early stage. Problems with stability, charging speed and manufacture must be overcome." They note that future anodes could be based on silicon, also noted by IEA:

> *"Combining conversion cathodes with silicon anodes in the next generation of lithium-ion battery cells could allow cells to store more than twice as much energy as the best conventional ones by volume, and more than three times by weight. Half as many cells would be required to power electric vehicles, also halving costs, weight and volume.*
>
> *Silicon-anode technology is advancing. Tesla already uses small amounts of silicon in anodes made of graphite for lithium-ion cells in its electric vehicles, and BMW announced plans to incorporate silicon-dominant anodes in its future electric vehicle batteries. Other companies, too, are developing silicon-rich anode materials. These include the Californian firms Enevate in Irvine, Enovix in Fremont and Sila Nanotechnologies in Alameda (G.Y. is a board member, shareholder and chief technology officer of Sila Nanotechnologies)."*[15]

[12] A solid-state battery replaces either the battery's electrodes, its liquid electrolyte, or both, with some type of solid like ceramic or glass. Because highly flammable materials are being replaced with something solid, the battery can withstand higher temperatures, which means higher capacity.

[13] See id. "Solid-state batteries are the next step on major OEM's roadmaps (see e.g. example Volkswagen), they are an enabler for doubling the driving range, they would have better safety and would be denser thus allow potential reductions in the amount of passive components." See also ADL at footnote 2.

[14] Turcheniuk, et al., " Ten Years Left to Redesign Lithium-Ion Batteries," Nature 559, 467-470 (2018) doi: 10.1038/d41586-018-05752-3 at https://www.nature.com/articles/d41586-018-05752-3.

[15] See id.

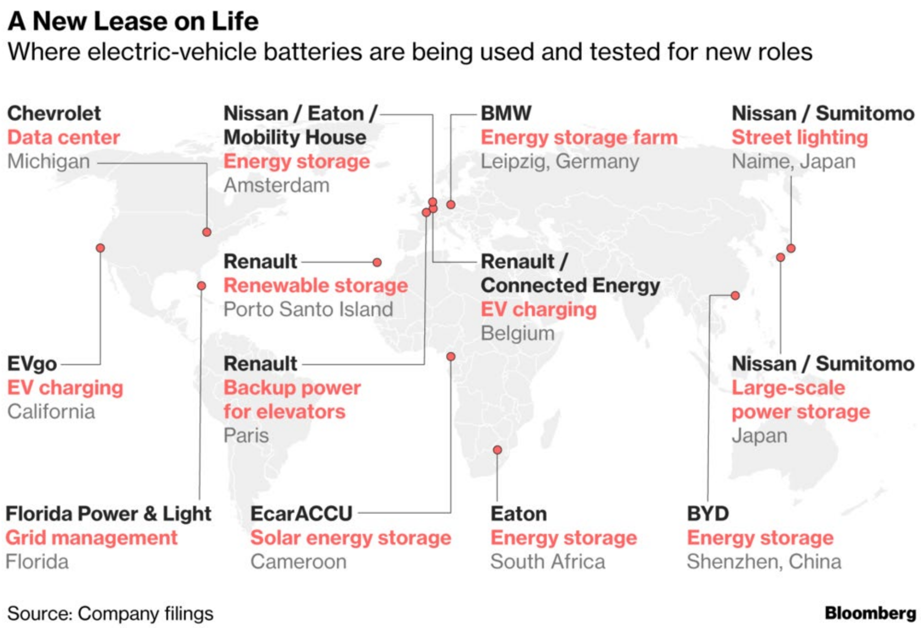
As Figure 2 above shows, Li-ion technology might be overtaken by other battery designs that boast higher theoretical energy densities as well as lower theoretical costs. Examples include Li-air and Lisulfur batteries. However, according to IEA, their technology readiness level is very low, practical performance has yet to be tested and the performance advantage over lithium-ion is still unproven.

Even if battery cells with substantially different designs were to become available in the market by 2030, a time lag due to the need to build up production capacity would delay wide availability on the market for these advanced technologies. This is why most batteries are expected to belong to the “Next generation” technology class in 2030.

Battery Recycling

In 2018, about 100,000 metric tons of lithium-ion batteries were recycled globally and about 14,000 metric tons of cobalt was recovered from batteries, or about one-fifth of the market for the metal.[16] Finding ways to reuse the technology is becoming more urgent as the global stockpile of EV batteries is forecast to exceed the equivalent of about 3.4 million packs by 2025, compared with about 55,000 this year, according to calculations based on Bloomberg NEF data.[17] The cumulative capacity of used EV batteries is expected to be about 200 GWh by 2025. The battery, when removed from an EV, still retains 50-70% of its capacity — so imagine the challenge, but also the opportunity: what do you do with thousands (or eventually millions) of these used batteries around the world? Right now, repurposing batteries is not cheap.

Figure 4: Global EV Battery Recycling Initiatives



[16] Tammy Webber, Chicago Tribune, "Argonne Lab Leading U.S. Push on Lithium Batteries: 'If We Don't Recycle, We Will Run Out of Materials,'" Mar. 20, 2019 available at https://www.chicagotribune.com/business/ct-biz-lithium-ion-battery-recycling-20190218-story.html.

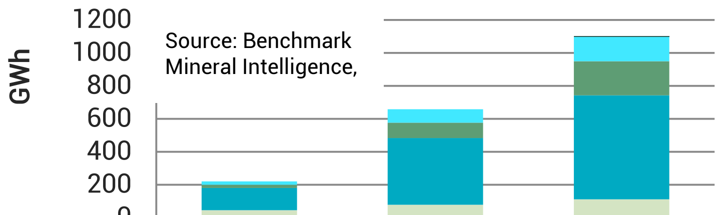
[17] Stringer and Ma, "Where 3 Million Electric Vehicle Batteries Will Go When They Retire," June 27, 2018 available at https://www.bloomberg.com/news/features/2018-06-27/where-3-million-electric-vehicle-batteries-will-go-when-they-retire. “A lithium-ion battery actually never dies,” said Hans Eric Melin, founder of London-based Circular Energy Storage Research and Consulting. “It's just like you can take an alkaline battery out of your flashlight and put it into a remote control, and it'll still be good enough.”

Just this month, the U.S. Department of Energy (DOE) announced a US$15 million effort to develop technologies to recycle used batteries calling it a national security issue because of U.S. dependence on lithium, cobalt and other metals.[18] The EU and China have similar initiatives. In addition, China and the EU already have regulations in place governing the recycling of batteries, and the U.S. is expected to follow. However, it's difficult to develop a standard procedure to recycle LIBs because their chemical composition varies so much. Some are developed for their power, some for energy density, and others for their longevity.

Compared to other types of batteries, such as lead acid, this variety makes LIB recycling much more complicated, and therefore expensive. Some plants use pyrometallurgy, in which all LIBs that arrive at the facility are smelted. The alloy of cobalt, nickel, and copper obtained from this melt can then be processed back into the individual metals or the precursors needed for making battery materials, such as cobalt carbonate. But the reality is it is more expensive to recycle a material like lithium than it is to mine it. Meantime, the auto industry, lead by Renault, Nissan, GM, BMW, Toyota and BYD as well as some renewable-energy storage suppliers are looking at ways to reuse and recycle batteries for other uses, creating an aftermarket and additional margin on them. Figure 4 summarizes some of those efforts. Tesla is focused on recovering used battery materials.

Battery Megafactories

Figure 5: LIB Battery Production Capacity, 2018-2028



	2018	2023	2028
Other	0	0	5
North America	20.9	81	148
Europe	19.6	93.5	207
China	134.5	405	631
Asia (excl China)	45.5	78.5	111.5

In just a decade, LIB megafactories around the world will have a combined production capacity equivalent to 22 Tesla Gigafactories. The majority of this capacity will be located in China, which is projected to have 57% of the global total. An analysis from Benchmark Mineral Intelligence forecasts a 399% increase in LIB production capacity over the next decade – enough to pass the impressive 1 TWh milestone.[19] Figure 5 summarizes this analysis for 2018-2028.

[18] See id. at footnote 13.

[19] "The global energy-storage market will surge to a cumulative 942 gigawatts by 2040, according to a new forecast from Bloomberg NEF published Tuesday, and that growth will necessitate $1.2 trillion in investment. Sharply falling battery costs is a key driver of the boom. BNEF sees the capital cost of a utility-scale lithium-ion storage system falling 52% by 2030." See Bloomberg, " Battery Boom Is Expected to Attract $1.2 Trillion in Investment by 2040," Nov. 6, 2018 at https://www.latimes.com/business/technology/la-fi-tn-batteries-20181106-story.html.

The top 10 megafactories represent 299 GWh of capacity in 2023, which will be equal to almost half of the global production total, according to Benchmark Intelligence. Table 1 ranks the top 10 plants by projected capacity. Of the top 10 megafactory plants in 2023, the majority will be located in China; the U.S. (Tesla Gigafactory), South Korea (Samsung), and Poland (LG Chem) will be home to the rest.

Table 1: Top 10 Megafactory Plants

Rank	Megafactory	Owner	Country	Forecasted Capacity by 2023 (GWh)
#1	CATL	Contemporary Amperex Technology Co Ltd	China	50
#2	Tesla Gigafactory 1	Tesla / Panasonic Corp (25%)	U.S.	50
#3	Nanjing LG Chem New Energy Battery Co., Ltd.	LG Chem	China	35
#4	Nanjing LG Chem New Energy Battery Co., Ltd. Plant 2	LG Chem	China	28
#5	Samsung SDI Xian	Samsung SDI	China	25
#6	Funeng Technology	Funeng Technology (Ganzhou)	China	25
#7	BYD , Qinghai	BYD Co Ltd	China	24
#8	LG Chem Wroclaw Energy Sp. z o.o.	LG Chem	Poland	22
#9	Samsung SDI Korea	Samsung SDI	Korea	20
#10	Lishen	TianJin Lishen Battery Joint-Stock CO., LTD	China	20

Source: Benchmark Mineral Intelligence, October 2018

Conclusion

In summary, I am in agreement based on research and discussions with experts in the space that battery prices are going to continue declining. LIBs will remain the battery of choice until 2030 (and possibly beyond) and there will be incremental improvements to them that will make them more efficient and cost-effective and avoid the issues raised by mining cobalt in the DRC and price volatility if supplies become limited. There will most likely be enough lithium. Gigafactories will be built, batteries will even more mass produced and the recycling regime will be figured out. The issues surrounding batteries appear surmountable. But, make no mistake, the resource dependencies are simply being switched: from fossil fuels to minerals and rare earths. That did not concern the experts I spoke to, but that does not mean it is not a valid concern. Lastly, while not the subject of this report, the massive factory expansions/constructions planned does raise issues of climate/environment sustainability. While Tesla will run its Gigafactories on solar with batteries as back up storage, other plants, most likely in China will not.